GRADUATE AERONAUTICAL LABORATORIES
CALIFORNIA INSTITUTE OF TECHNOLOGY

FM 90-2

Three Samples of Inviscid Supersonic Reacting Nozzle Flow Calculation using SURF

by

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Pasadena

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Introduction

This report is a presentation of three calculations made using SURF. A modification to the program already implemented is discussed first. Then a summary of the results is presented, followed by the plots of the flow fields. See the GALCIT report FM 89-1 entitled "Surf: A Program for Calculating Inviscid Supersonic Reacting Flows in Nozzles" by Martin Rein for more details and a description of the program.

Modification of the THDYN subroutine

The SURF program was used to compute three cases of non-equilibrium flow in the T5 nozzle. The input data files are identical except for the value of the reservoir temperature.

Case 1: T_o = 4795 K, p_o = 100 MPa
Case 1: T_o = 5900 K, p_o = 100 MPa
Case 1: T_o = 7260 K, p_o = 100 MPa

A convergence problem was encountered for the first two cases. The temperature is too low with respect to the pressure and this leads to a frozen flow situation downstream of the nozzle (for instance, with T_o = 4795 K, T drops to 700 K at x = 0.7 m). The problem was with the right hand side of equation 2.16 of Martin Rein's report:

$$\frac{d\gamma_j}{dt} = \sum_{k=1}^{r} P_{jk} \quad , \qquad j = c+1, \ldots, s \tag{2.15}$$

where

$$P_{jk} := \rho^{(\sum_{l=1}^{s} \nu_{lk})-1} \beta_{jk}\, k_{f,k} \left[\prod_{l=1}^{s} \gamma_l^{\nu_{lk}} - \frac{1}{K_{\gamma,k}} \prod_{l=1}^{s} \gamma_l^{\nu'_{lk}} \right] \quad , \quad j = c+1, \ldots, s \quad , \quad k = 1, \ldots, r \tag{2.16}$$

P_{jk} was rearranged as follows. The rate constant $k_{f,k}$ was drawn into the bracket. The expression for the rate constant includes an exponential function, as does the equilibrium contant $K_{\gamma,k}$.

$$k_{f,k} = C_{f,k} \cdot T^{\eta_{f,k}} \cdot exp(-\Theta_{a,k}/T) \quad , \qquad k = 1, \ldots, r \tag{2.14}$$

The argument of one of these functions is positive while the other is negative (the equilibrium constant is in the donominator). The arguments of the exponential function are now added and thereafter the exponential expression is computed. In this manner, an overflow is avoided. All the changes were implemented more specifically in the THDYN subroutine.

Presentation of the results

A full 2-D non-equilibrium calculation was performed everywhere in the axisymmetric nozzle. For each case, the input data file (based on Appendix D of Martin Rein's report) precedes the correponding output summary file. The latter is self-explanatory. Then the streamwise (along the centerline and along the wall) and contour plots of various fields variables complete each set.

Some contour plots are not included because the corresponding variables are fairly constant (such as γ_{AR}, γ_{N_2}, γ_{O_2}, etc.) throughout the nozzle. The streamwise plots have all the same scale to allow comparison and therefore some curves appear incomplete (or not at all) such as γ_{NO+} and γ_N which have very low values.

Summary of results

The following table lists the values of some variables for each case for comparison purpose.

p_o = 100MPa		case 1	case 2	case 3
T_o	(K)	4795	5900	7260
h_o	(MJ/kg)	6.77	9.22	12.48
ρ_o	(kg/m3)	70.53	54.78	41.89
$u_{1\ cm}$	(m/s)	1706	1896	2221
$u_{1\ m}{}^*$	(m/s)	3323	3869	4433
$p_{1\ cm}$	(MPa)	32.10	33.13	31.65
$p_{1\ m}{}^*$	(kPa)	18.74	28.37	38.01
$\rho_{1\ cm}$	(kg/m3)	27.79	22.11	16.51
$\rho_{1\ m}{}^*$	(kg/m3)	0.114	0.097	0.079

*along the centerline

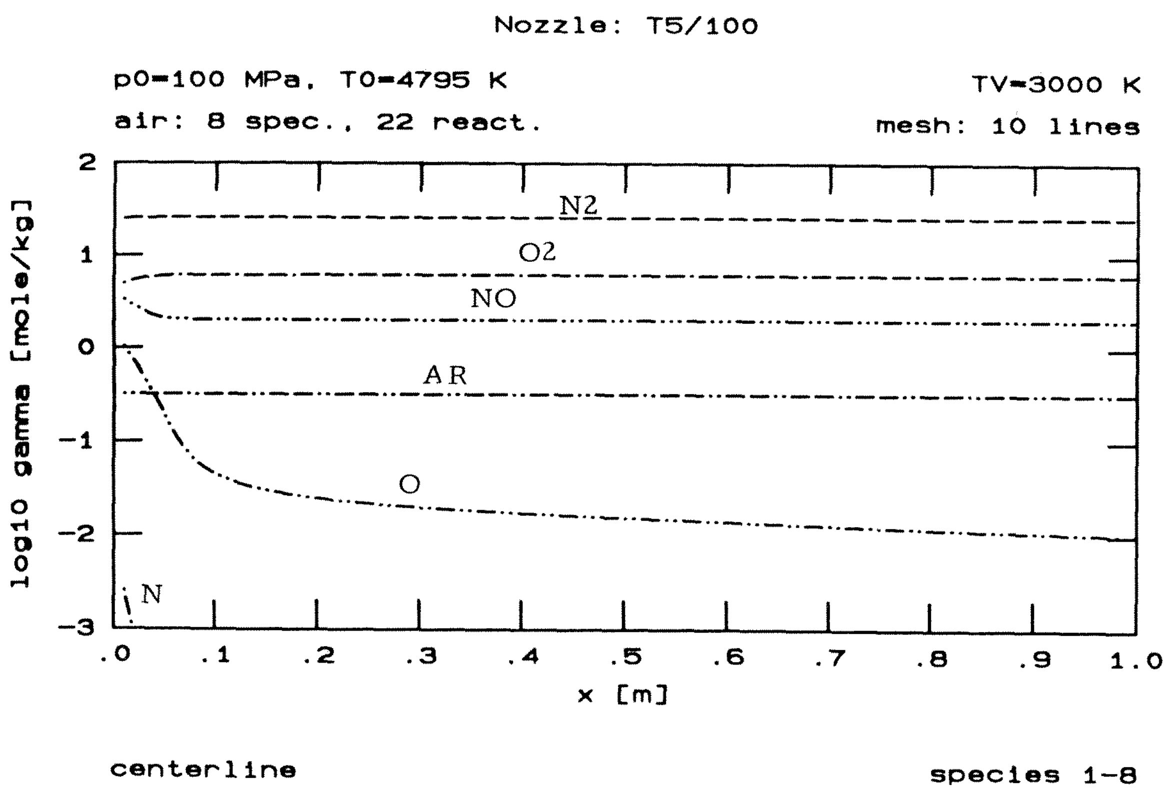
```
Nozzle: T5/100 (GALCIT)
expansion of air (8 species, 22 reactions)
names of output data files
air1bsum
air1bres
job id. no.,iequil,ifrzn,i2d,iout
1,0,0,1,0
xu,xd,mmax,nmax
0.01,1.0,150,10
T0,P0
4795.0,100.0e+06
Tv
3.0d3
ichkd,rminlt
1,2.0
dcrit
-1.0d-2
ic,is,ir
4,8,22
indep. species: symb(i), g0(i), i=1,.,ic
 E- ,0.0d0
 N2 ,0.78112d0
 O2 ,0.20954d0
 AR ,0.00934d0
alph(j,i), j=ic+1,.,is, i=1,.,ic
0.0,0.5,0.0,0.0
0.0,0.0,0.5,0.0
0.0,0.5,0.5,0.0
-1.0,0.5,0.5,0.0
thermodynamic properties of (is) species:
 E-
5.4847d-7,1,0.0e0,5.0d3
1.0,1.0,1,0
2.0
0.0e0
0.0e0
20.78675d0,0.0d0,0.0d0,0.0d0,0.0d0,
-97.57301d0
 N2
28.0160d-3,2,0.0e0,5.0d3
2.86,2.0,4,1
1.0,3.0,6.0,1.0
0.0e0,72352.91,85843.07,88323.06
3353.24
28.69805d0,5.1357108d-3,-1.0604805d-6,9.1105665d-11,-2.27333721d-15,
25.53668d0
 O2
32.0d-3,2,0.0e0,5.0d3
2.07,2.0,5,1
3.0,2.0,1.0,3.0,3.0
0.0e0,11096.78,18996.51,51965.59,71700.80
2238.97
27.01839d0,8.253918d-3,-1.6716921d-6,1.4778012d-10,-4.1585184d-15,
49.18163
 AR
39.944d-3,1,0.0e0,5.0d3
1.0,1.0,3,0
1.0,5.0,3.0
0.0e0,134099.5,134973.2
0.0e0
21.31292d0,-5.9728982d-4,1.8631269d-7,-2.2439826d-11,9.2875987d-16,
33.26661d0
 N
14.008d-3,1,471243.3268,5.0d3
```

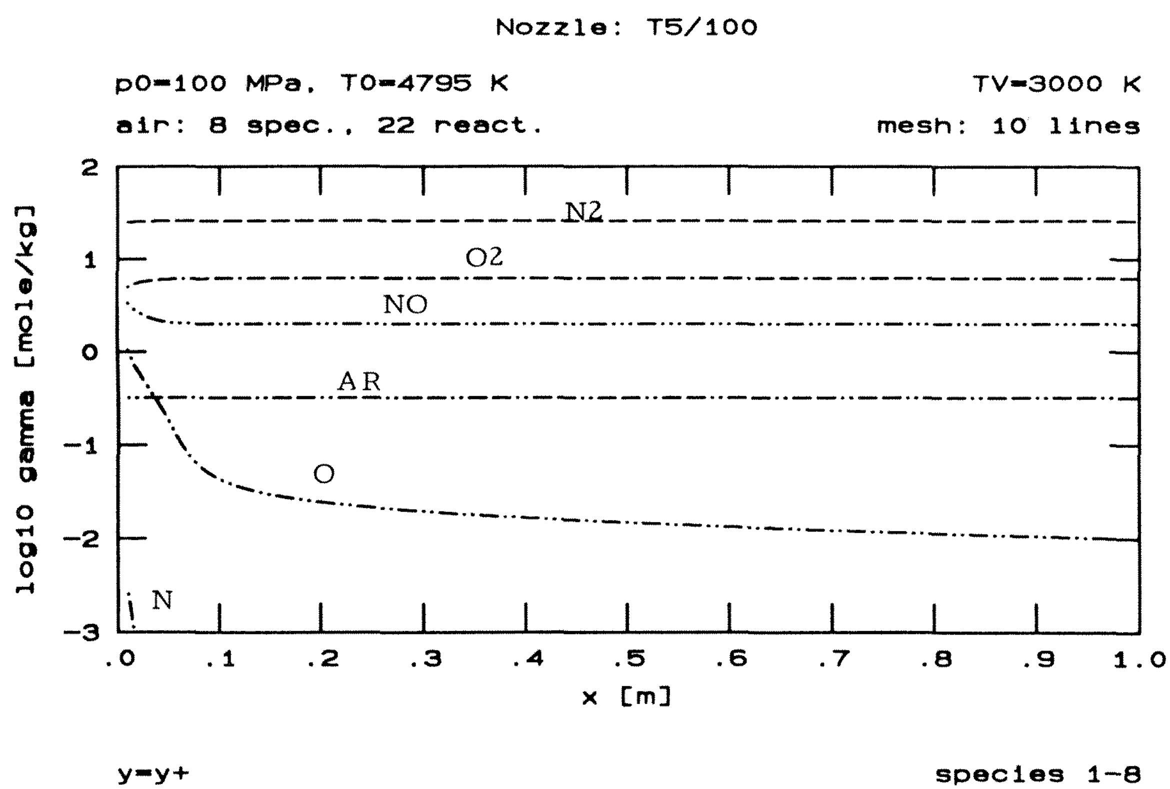
```
1.0,1.0,5,0
4.0,6.0,4.0,6.0,12.0
0.0e0,27682.28,27758.32,41520.40,119951.2
0.0e0
25.01829,-5.212693d-3,1.574425d-6,-1.3852965d-10,3.880839d-15,
10.83801d0
 O
16.0d-3,1,246857.841,5.0d3
1.0,1.0,6,0
5.0,3.0,1.0,5.0,1.0
5.0
0.0e0,228.9249,326.7953,22845.16,48650.7
106202.7
0.0e0
21.56952d0,-8.3295238d-4,2.99205d-7,-2.8873997d-11,8.9304039d-16,
38.25274d0
 NO
30.008d-3,2,89890.90965,5.0d3
2.42,1.0,3,1
4.0,2.0,4.0
0.0e0,63296.52,66107.84
2699.18
31.23181d0,3.4655021d-3,-6.5841147d-7,5.6218415d-11,-1.5014366d-15,
30.02577d0
 NO+
30.00765d-3,2,984961.9485,5.0d3
2.42,1.0,6,1
1.0,6.0,3.0,6.0,2.0
0.0e0
0.0e0,58025.33,85093.78,105107.5,105539.5
0.0e0
3372.95
28.24824d0,6.2350007d-3,-1.512119d-6,1.5423789d-10,-4.6051132d-15,
34.92642d0
ibet(l,k), l=1,.,is, k=1,.,ir:
0 2 0 0 0 0 0 0
0 1 0 0 1 0 0 0
0 1 1 0 0 0 0 0
0 1 0 1 0 0 0 0
0 1 0 0 0 1 0 0
0 1 0 0 0 0 1 0
0 0 2 0 0 0 0 0
0 0 1 0 0 1 0 0
0 1 1 0 0 0 0 0
0 0 1 1 0 0 0 0
0 0 1 0 1 0 0 0
0 0 1 0 0 0 1 0
0 1 0 0 0 0 1 0
0 0 1 0 0 0 1 0
0 0 0 1 0 0 1 0
0 0 0 0 1 0 1 0
0 0 0 0 0 1 1 0
0 0 0 0 0 0 2 0
0 0 1 0 1 0 0 0
0 1 0 0 0 1 0 0
0 1 1 0 0 0 0 0
1 0 0 0 0 0 0 1
irnp(l,k), l=1,.,is, k=1,.,ir:
0 1 0 0 2 0 0 0
0 0 0 0 3 0 0 0
0 0 1 0 2 0 0 0
0 0 0 1 2 0 0 0
0 0 0 0 2 1 0 0
0 0 0 0 2 0 1 0
```

```
0 0 1 0 0 2 0 0
0 0 0 0 0 3 0 0
0 1 0 0 0 2 0 0
0 0 0 1 0 2 0 0
0 0 0 0 1 2 0 0
0 0 0 0 0 2 1 0
0 1 0 0 1 1 0 0
0 0 1 0 1 1 0 0
0 0 0 1 1 1 0 0
0 0 0 0 2 1 0 0
0 0 0 0 1 2 0 0
0 0 0 0 1 1 1 0
0 0 0 0 0 1 1 0
0 0 0 0 1 0 1 0
0 0 0 0 0 0 2 0
0 0 0 0 1 1 0 0
rk1(k), rk2(k), rk3(k), k=1,.,ir:
3.0000000e+15,-1.5,1.132942e5
1.4999999e+16,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
3.6000000e+15,-1.5,5.939902e4
2.0999999e+12,-0.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
1000000.0,0.5,3.625576e3
5.0000000e+07,0.0,3.802827e4
9.1000002e+18,-2.5,6.501867e4
1.8000000e+15,-1.5,0.0e0
ithb(k), k=1,.,ir:
1,1,1,1,1,1,2,2,2,2,2,2,3,3,3,3,3,3,0,0,0,0
```

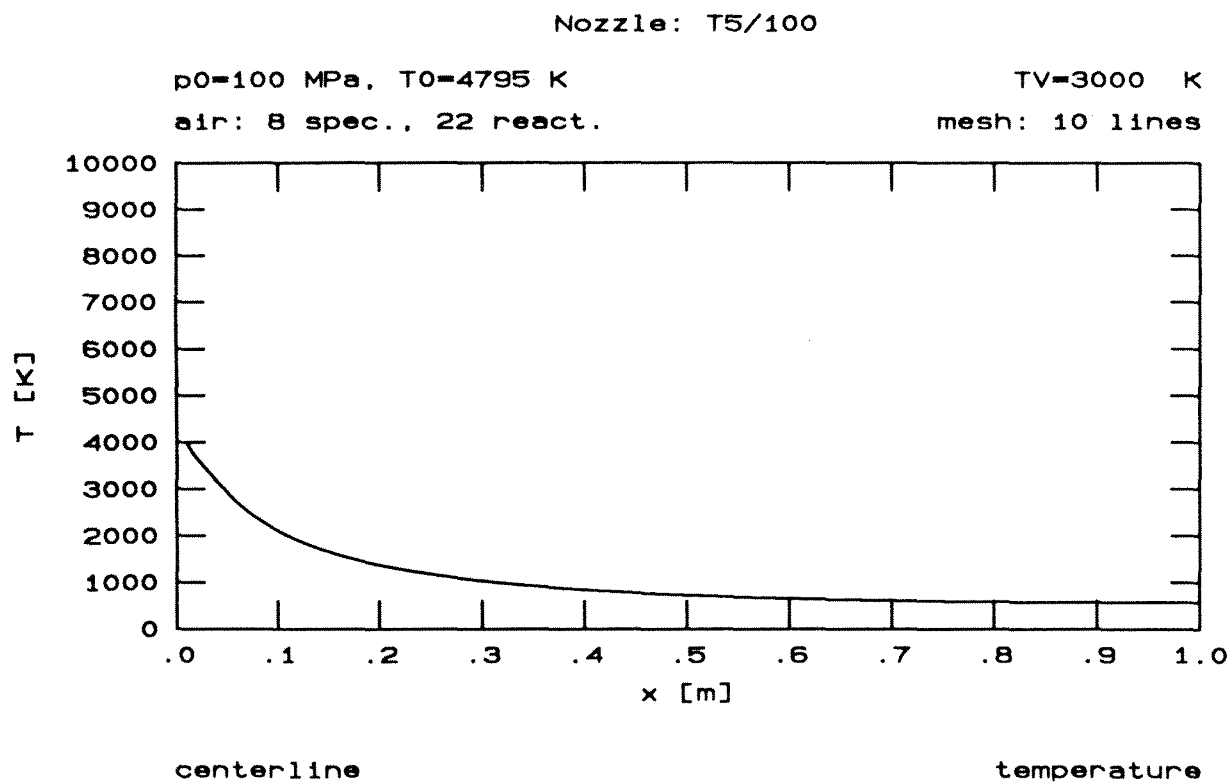
```
Nozzle: T5/100 (GALCIT)
expansion of air (8 species, 22 reactions)
---------------------------------------------------
JOBID =        1
---------------------------------------------------
name of output file 'outpt2':air1bres
---------------------------------------------------
to be calculated is/are:
                          two-dimensional nonequilibrium flow solution:
                             -fully nonequilibrium calculation
                             -initial conditions via 1-D equilibrium flow
* choked flow *
* vibrational modes frozen for temperature  T < Tv=  0.3000E+04 K
upstream/downstream boundary of flow field: xu=0.1000E-01 m, xd=0.1000E+01 m
grid lines in xi/eta direction             : mmax= 150,  nmax=  10
---------------------------------------------------
reservoir temperature and pressure: T0 =  0.4795E+04 K, p0 =  0.1000E+09 Pa
---------------------------------------------------
number of independent/dependent species: ic=   4  is=   8
independent species and their mole fractions (in case that no other species
are present):
              E-          0.0000E+00
              N2          0.7811E+00
              O2          0.2095E+00
              AR          0.9340E-02
---------------------------------------------------
dependent species:
              N
              O
              NO
              NO+
---------------------------------------------------
g0(i), i=1,...,ic, [mol/kg] (concentrations of independent species
  (when only independent species are present)):
  0.0000E+00  0.2697E+02  0.7235E+01  0.3225E+00
g0(j), j=ic+1,...,is, [mol/kg] (absolute maximum concentrations of
  dependent species):
  0.5394E+02  0.1447E+02  0.1447E+02  0.1447E+02
---------------------------------------------------
equilibrium reservoir state:
T0 =    0.4795E+04 K,     p0 =    0.1000E+09 Pa, rho0 =    0.7053E+02 kg/m**3
h0 =    0.6769E+07 J/kg, s0 =    0.8357E+04 J/(kgK)
species concentrations [mol/kg] (reservoir):
  0.8149E-04  0.2464E+02  0.3884E+01  0.3225E+00  0.1882E-01  0.2056E+01
  0.4647E+01  0.8149E-04
---------------------------------------------------
two-dimensional nozzle flow solution: choked flow
initial conditions at xu =   0.100000E-01m (area =   0.115597E+01)
   n            u [m/s]      v [m/s]      p [Pa]       rho [kg/m**3]
  g(j), j= ic+1,...,is [mol/kg]
   1            0.1706E+04  0.0000E+00  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
   2            0.1706E+04  0.4206E+02  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
   3            0.1704E+04  0.8403E+02  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
   4            0.1702E+04  0.1259E+03  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
   5            0.1698E+04  0.1675E+03  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
   6            0.1694E+04  0.2088E+03  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
   7            0.1688E+04  0.2497E+03  0.3210E+08  0.2779E+02
  0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
```

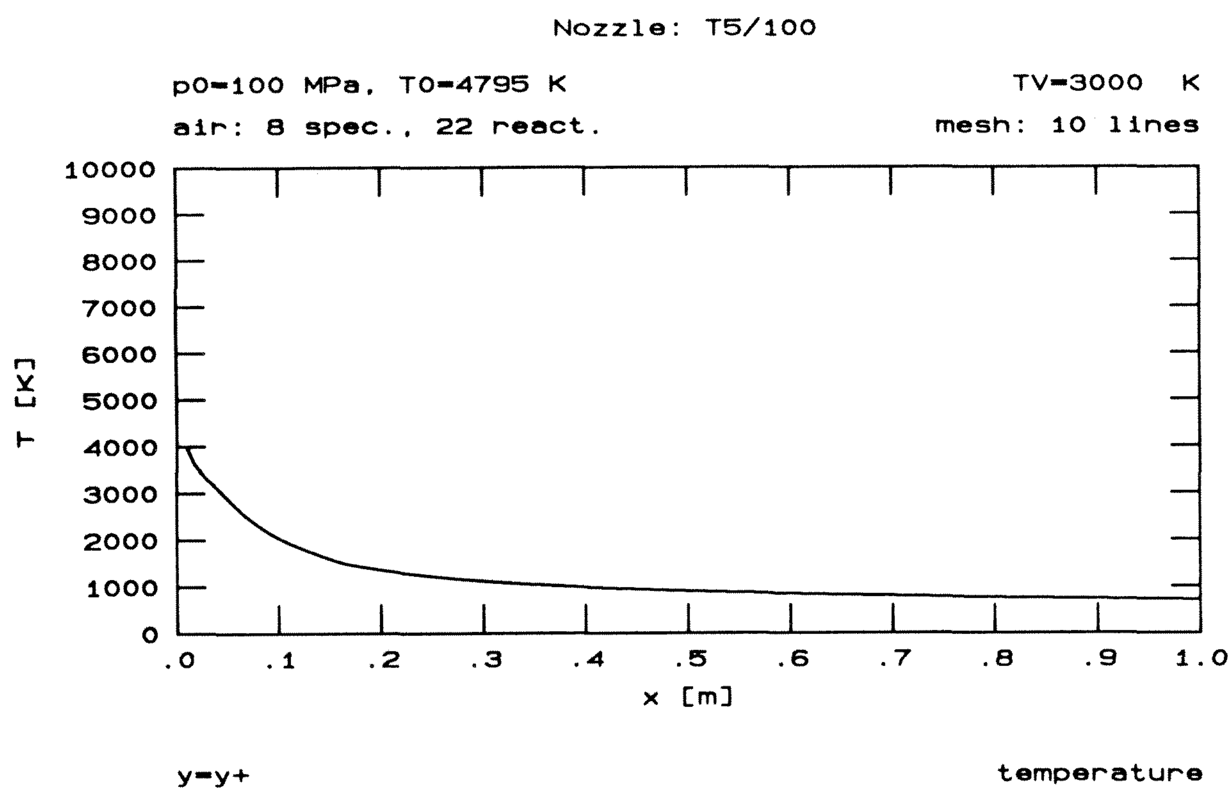
```
  8            0.1682E+04  0.2902E+03  0.3210E+08  0.2779E+02
 0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
  9            0.1674E+04  0.3302E+03  0.3210E+08  0.2779E+02
 0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
 10            0.1666E+04  0.3696E+03  0.3210E+08  0.2779E+02
 0.2567E-02  0.1048E+01  0.3376E+01  0.9146E-05
..............................................
***
*** fully nonequilibrium flow calculation starts right at the
*** upstream boundary (at x=xu)
***
solution at xd =   0.100000E+01 m (area =   0.109644E+03)
  n            u [m/s]     v [m/s]     p [Pa]      rho [kg/m**3]
 g(j), j= ic+1,...,is [mol/kg]
  1            0.3323E+04  0.0000E+00  0.1874E+05  0.1142E+00
 0.2036E-09  0.1020E-01  0.2047E+01  0.1120E-06
  2            0.3322E+04  0.2428E+01  0.1907E+05  0.1156E+00
 0.1999E-09  0.1021E-01  0.2046E+01  0.1118E-06
  3            0.3320E+04  0.6879E+01  0.2004E+05  0.1198E+00
 0.1899E-09  0.1023E-01  0.2043E+01  0.1111E-06
  4            0.3316E+04  0.1486E+02  0.2159E+05  0.1263E+00
 0.1757E-09  0.1026E-01  0.2039E+01  0.1101E-06
  5            0.3311E+04  0.2718E+02  0.2364E+05  0.1347E+00
 0.1594E-09  0.1028E-01  0.2034E+01  0.1088E-06
  6            0.3306E+04  0.4393E+02  0.2612E+05  0.1446E+00
 0.1427E-09  0.1029E-01  0.2028E+01  0.1072E-06
  7            0.3300E+04  0.6448E+02  0.2900E+05  0.1558E+00
 0.1267E-09  0.1026E-01  0.2023E+01  0.1053E-06
  8            0.3293E+04  0.8744E+02  0.3228E+05  0.1682E+00
 0.1117E-09  0.1020E-01  0.2019E+01  0.1032E-06
  9            0.3286E+04  0.1104E+03  0.3617E+05  0.1824E+00
 0.9756E-10  0.1009E-01  0.2017E+01  0.1010E-06
 10            0.3278E+04  0.1294E+03  0.4113E+05  0.2000E+00
 0.8378E-10  0.9926E-02  0.2017E+01  0.9866E-07
----------------------------------------------
```


Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
N2
O2
NO
AR
O
N
log10 gamma [mole/kg]
2
1
0
-1
-2
-3
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
species 1-8



Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 gamma [mole/kg]
2
1
0
-1
-2
-3
N2
O2
NO
AR
O
N
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
species 1-8


Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
T [K]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
temperature


Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
T [K]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
temperature

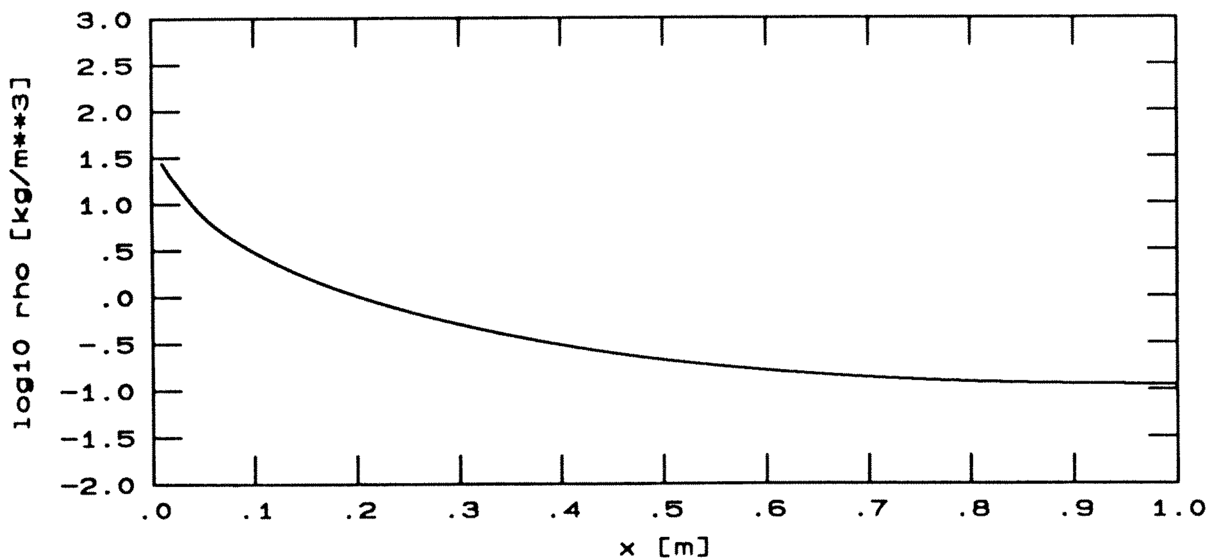
Nozzle T5/100

p0=100 MPa, T0=4795 K

TV=3000 K

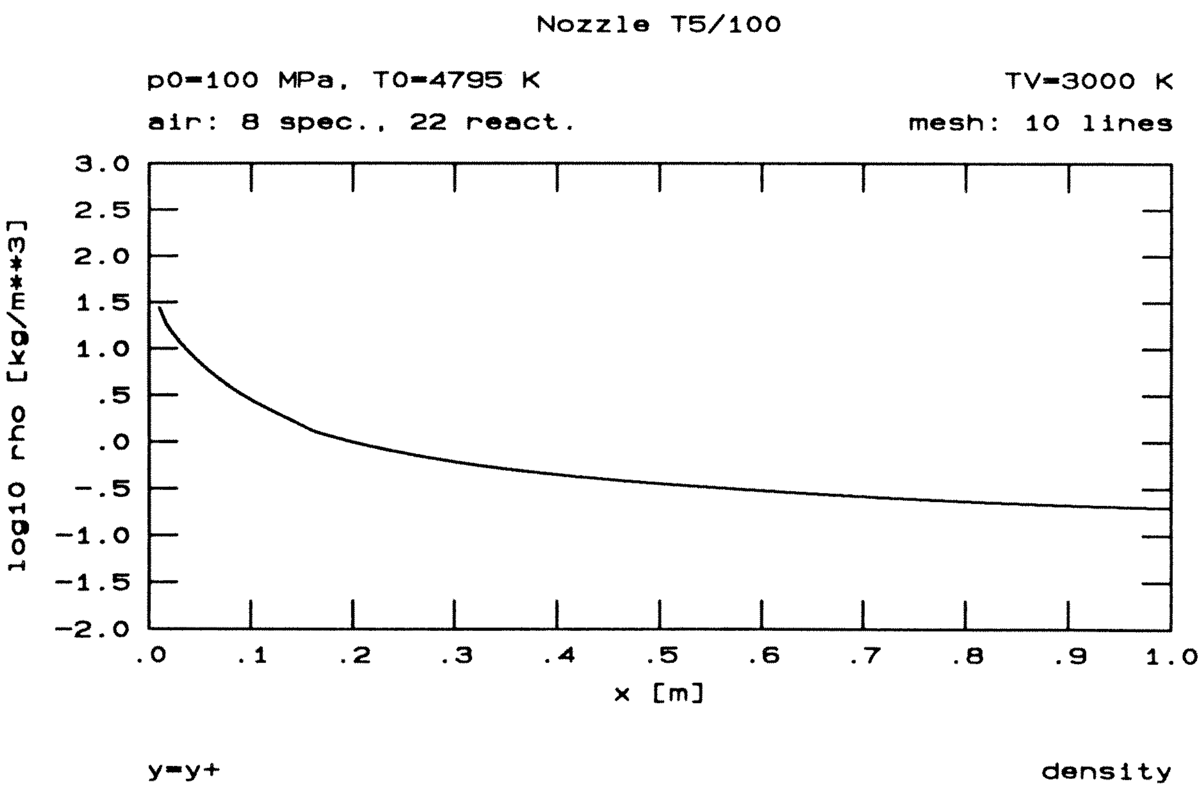
air: 8 spec., 22 react.

mesh: 10 lines

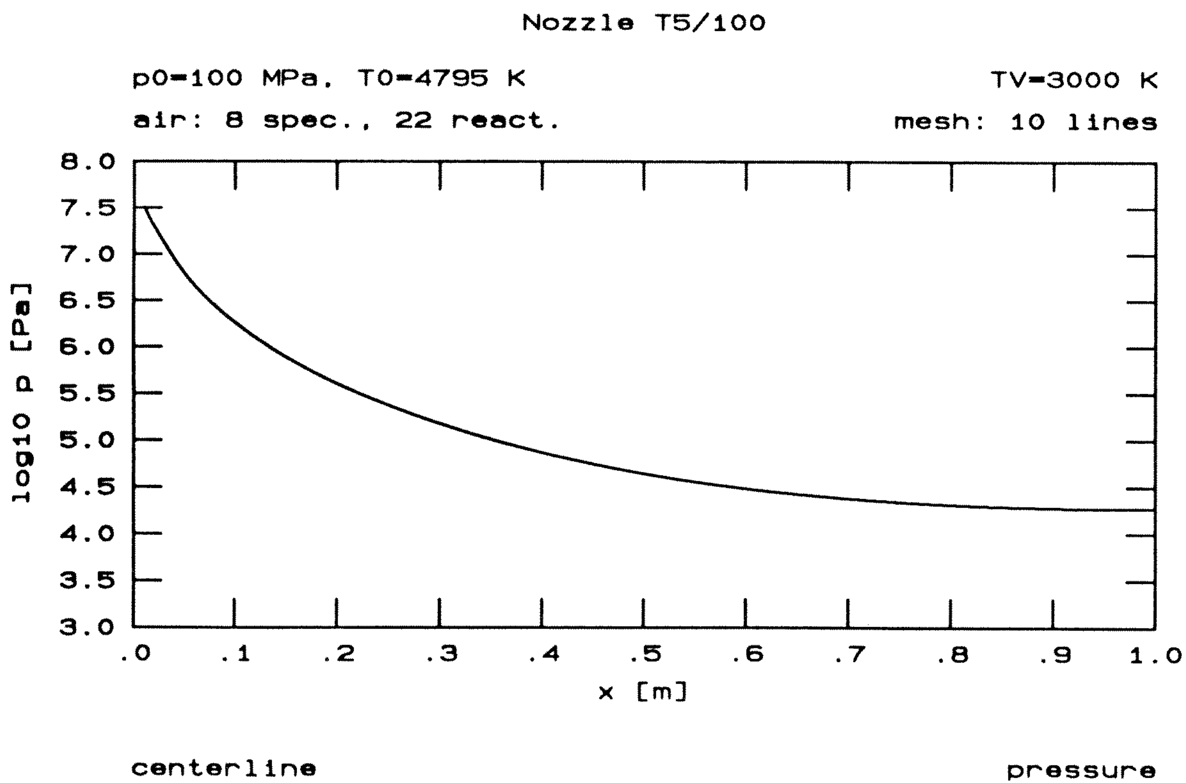


centerline

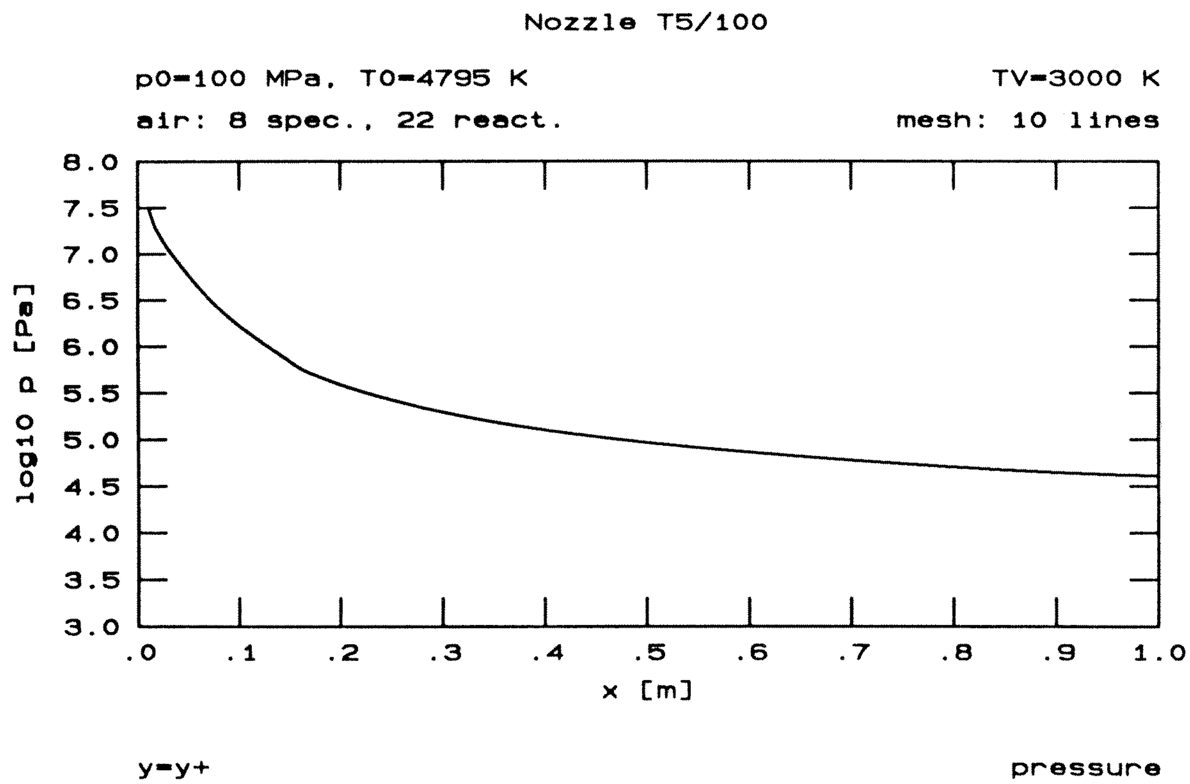
density



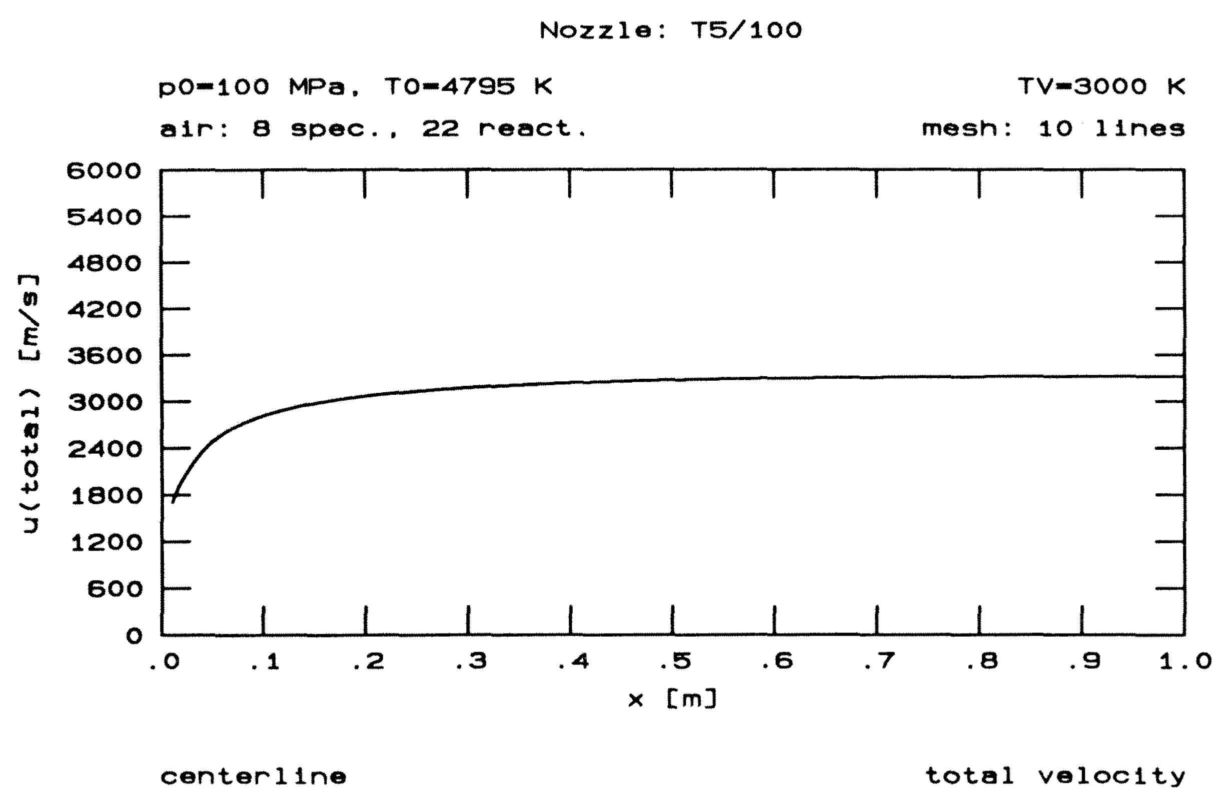
Nozzle T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 rho [kg/m**3]
3.0
2.5
2.0
1.5
1.0
.5
.0
-.5
-1.0
-1.5
-2.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
density

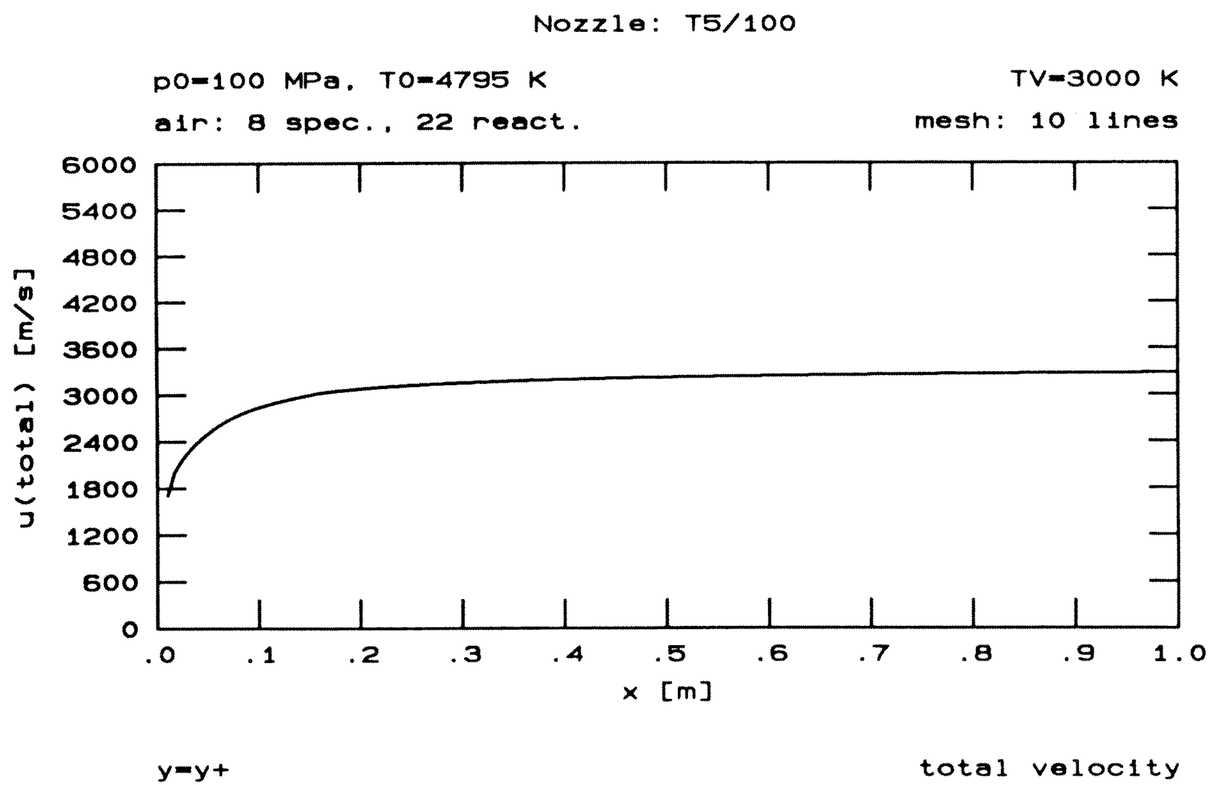


Nozzle T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 p [Pa]
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
pressure

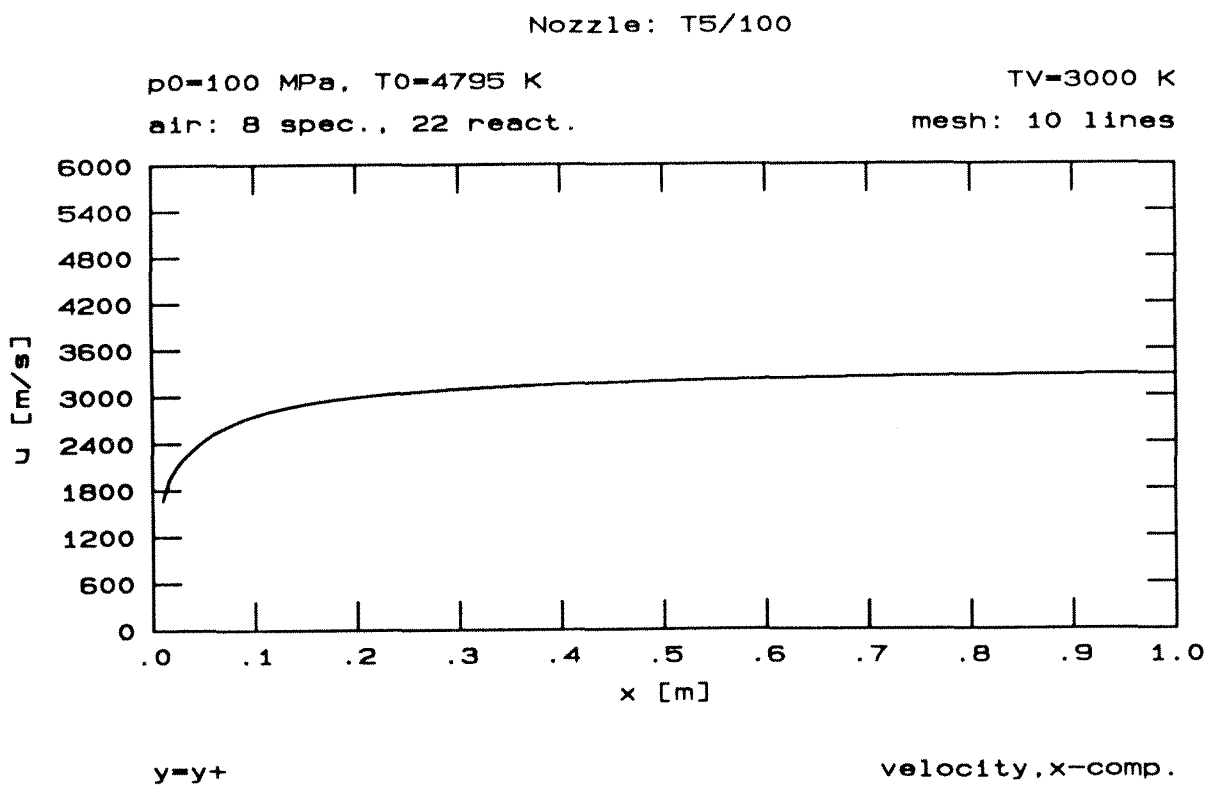


Nozzle T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 p [Pa]
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
pressure

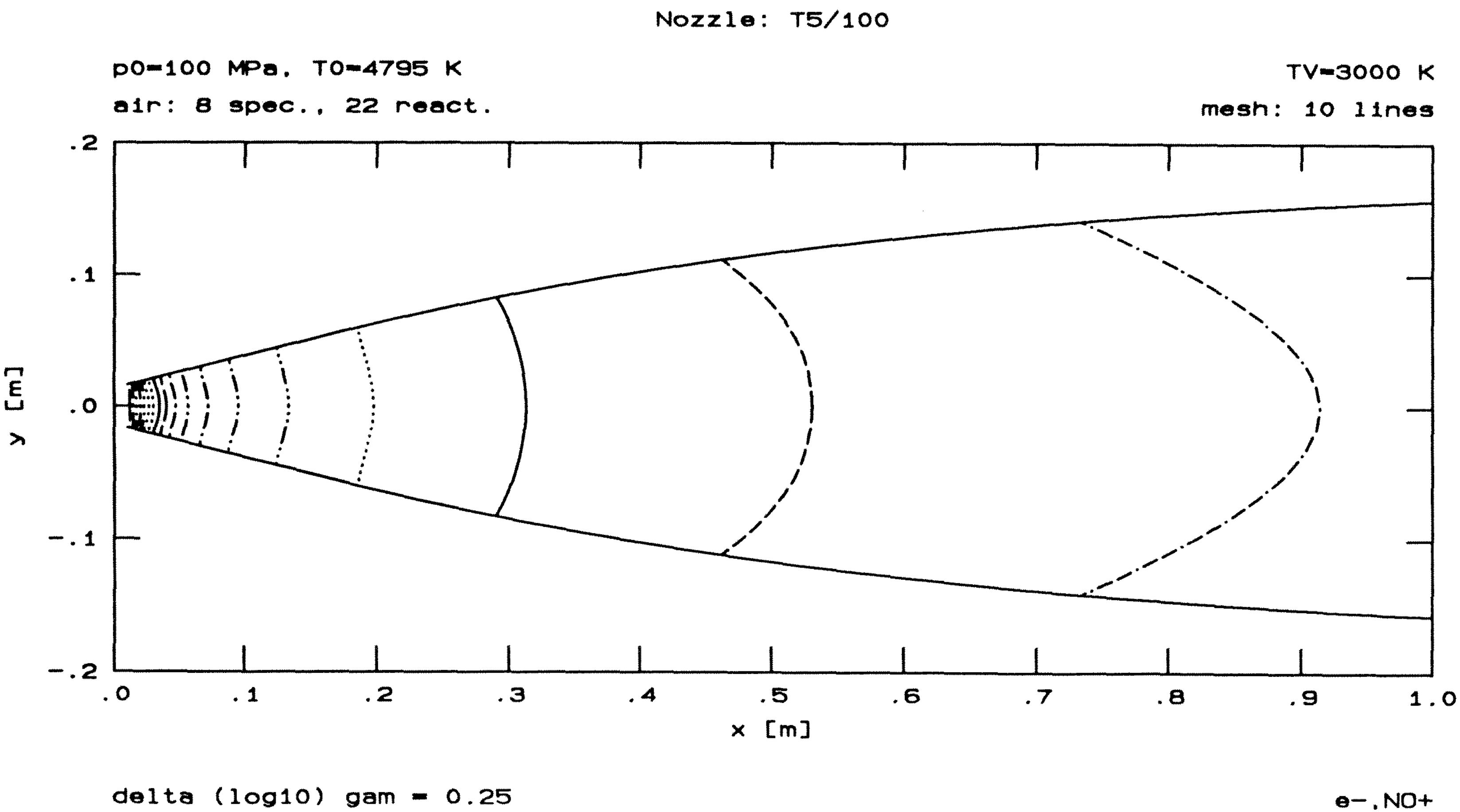

Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
u(total) [m/s]
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
total velocity



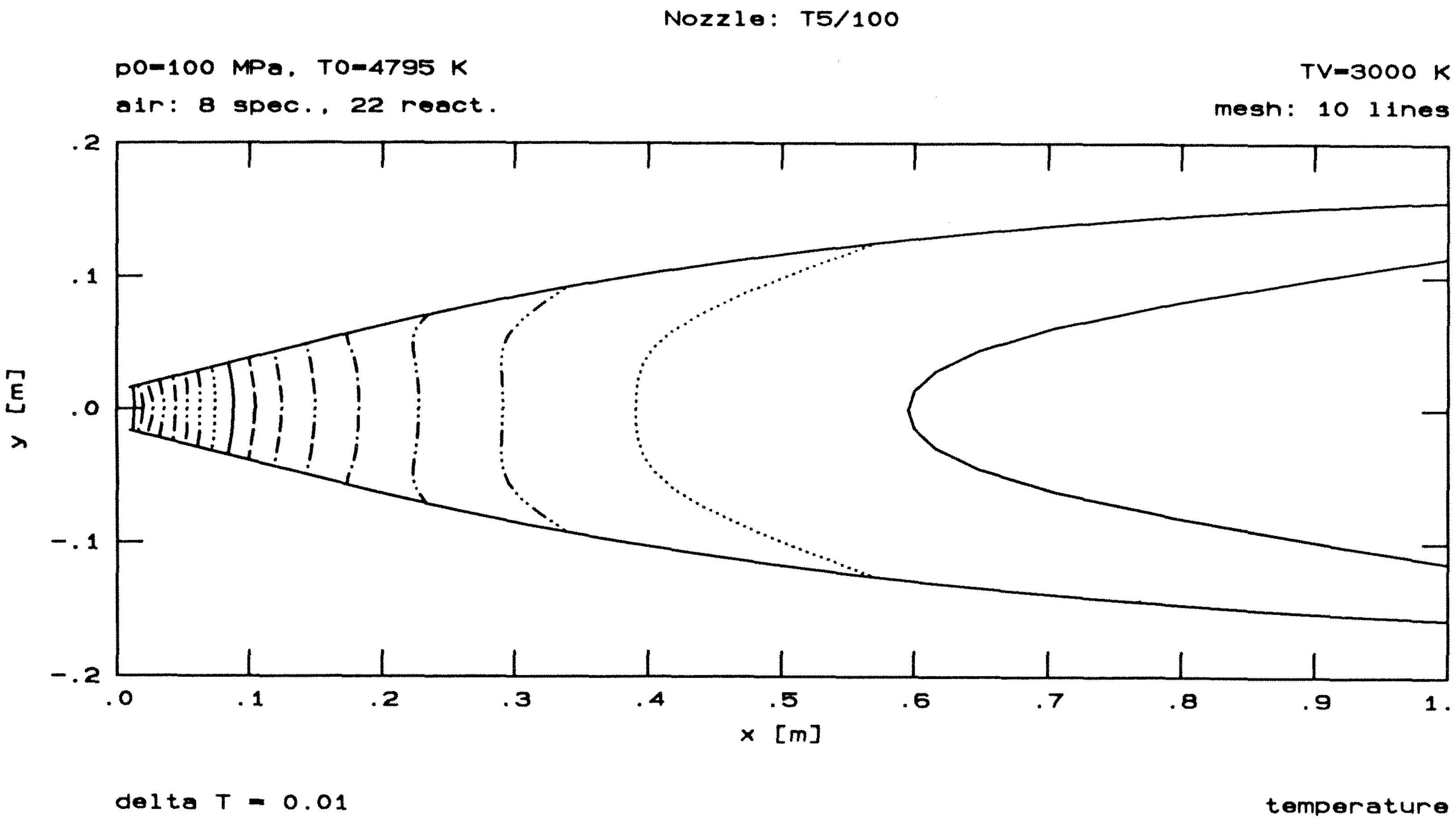
Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
u(total) [m/s]
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
total velocity



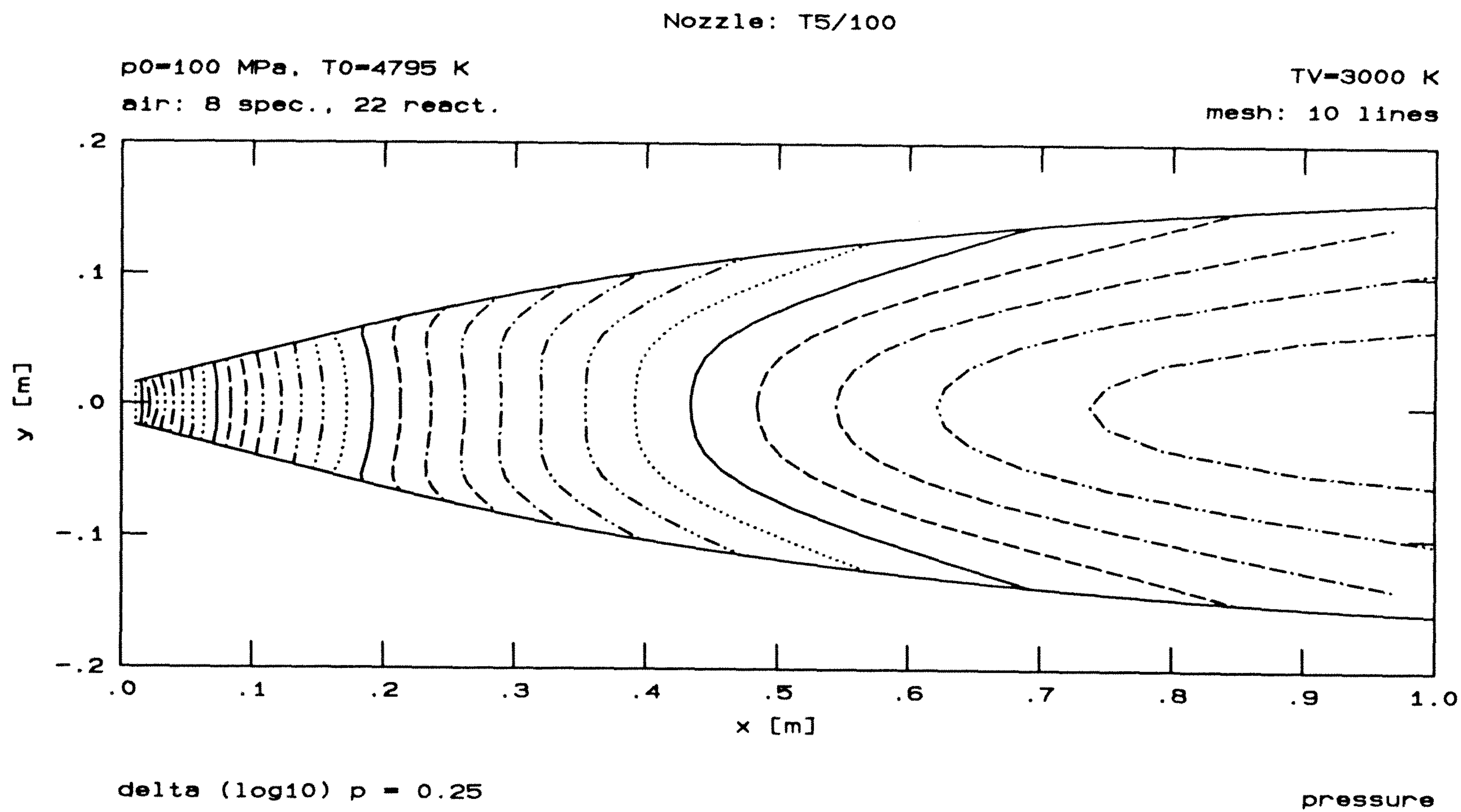
Nozzle: T5/100
p0=100 MPa, T0=4795 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
u [m/s]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
velocity,x-comp.



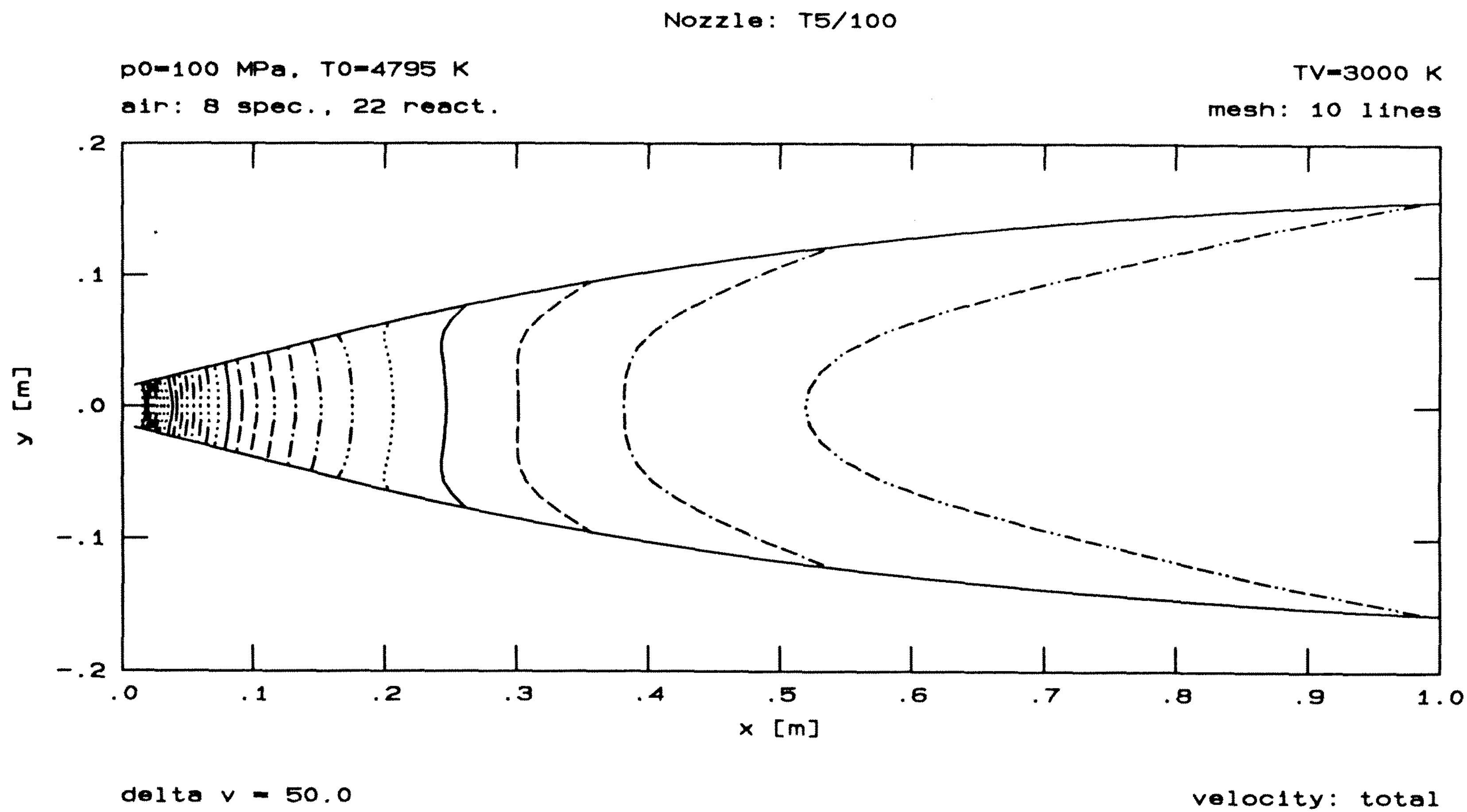
First upstream contour line: $\gamma_{NO+} = 8.2 \times 10^{-6}$ mol/kg;
farthest downstream one: $\gamma_{NO+} = 1.7 \times 10^{-7}$ mol/kg.



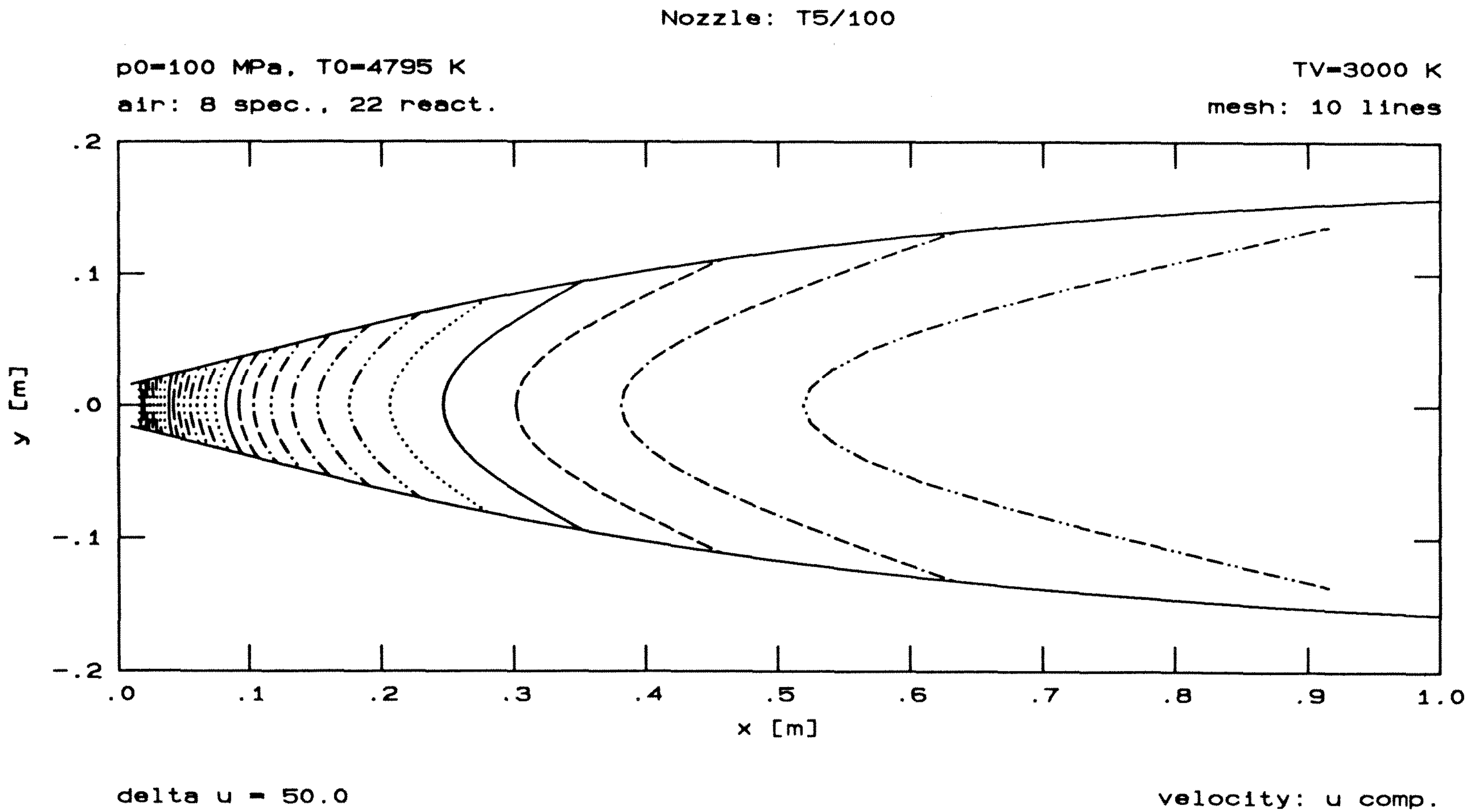
First upstream contour line: T = 3860 K;
farthest downstream one: T = 660 K.



First upstream contour line: p = 3.165 x 10^7 Pa;
farthest downstream one: p = 22477.01 Pa.



First upstream contour line: w = 1880 m/s;
farthest downstream one: w = 3280 m/s.



First upstream contour line: u = 1880 m/s;
farthest downstream one: u = 3280 m/s.

```
Nozzle: T5/100 (GALCIT)
expansion of air (8 species, 22 reactions)
names of output data files
air2bsum
air2bres
job id. no.,iequil,ifrzn,i2d,iout
2,0,0,1,0
xu,xd,mmax,nmax
0.01,1.0,150,10
T0,P0
5900.0,100.0e+06
Tv
3.0d3
ichkd,rminlt
1,2.0
dcrit
1.0d-2
ic,is,ir
4,8,22
indep. species: symb(i), g0(i), i=1,.,ic
 E- ,0.0d0
 N2 ,0.78112d0
 O2 ,0.20954d0
 AR ,0.00934d0
alph(j,i), j=ic+1,.,is, i=1,.,ic
0.0,0.5,0.0,0.0
0.0,0.0,0.5,0.0
0.0,0.5,0.5,0.0
-1.0,0.5,0.5,0.0
thermodynamic properties of (is) species:
 E-
5.4847d-7,1,0.0e0,5.0d3
1.0,1.0,1,0
2.0
0.0e0
0.0e0
20.78675d0,0.0d0,0.0d0,0.0d0,0.0d0,
-97.57301d0
 N2
28.0160d-3,2,0.0e0,5.0d3
2.86,2.0,4,1
1.0,3.0,6.0,1.0
0.0e0,72352.91,85843.07,88323.06
3353.24
28.69805d0,5.1357108d-3,-1.0604805d-6,9.1105665d-11,-2.27333721d-15,
25.53668d0
 O2
32.0d-3,2,0.0e0,5.0d3
2.07,2.0,5,1
3.0,2.0,1.0,3.0,3.0
0.0e0,11096.78,18996.51,51965.59,71700.80
2238.97
27.01839d0,8.253918d-3,-1.6716921d-6,1.4778012d-10,-4.1585184d-15,
49.18163
 AR
39.944d-3,1,0.0e0,5.0d3
1.0,1.0,3,0
1.0,5.0,3.0
0.0e0,134099.5,134973.2
0.0e0
21.31292d0,-5.9728982d-4,1.8631269d-7,-2.2439826d-11,9.2875987d-16,
33.26661d0
 N
14.008d-3,1,471243.3268,5.0d3
```

```
1.0,1.0,5,0
4.0,6.0,4.0,6.0,12.0
0.0e0,27682.28,27758.32,41520.40,119951.2
0.0e0
25.01829,-5.212693d-3,1.574425d-6,-1.3852965d-10,3.880839d-15,
10.83801d0
 O
16.0d-3,1,246857.841,5.0d3
1.0,1.0,6,0
5.0,3.0,1.0,5.0,1.0
5.0
0.0e0,228.9249,326.7953,22845.16,48650.7
106202.7
0.0e0
21.56952d0,-8.3295238d-4,2.99205d-7,-2.8873997d-11,8.9304039d-16,
38.25274d0
 NO
30.008d-3,2,89890.90965,5.0d3
2.42,1.0,3,1
4.0,2.0,4.0
0.0e0,63296.52,66107.84
2699.18
31.23181d0,3.4655021d-3,-6.5841147d-7,5.6218415d-11,-1.5014366d-15,
30.02577d0
 NO+
30.00765d-3,2,984961.9485,5.0d3
2.42,1.0,6,1
1.0,6.0,3.0,6.0,2.0
0.0e0
0.0e0,58025.33,85093.78,105107.5,105539.5
0.0e0
3372.95
28.24824d0,6.2350007d-3,-1.512119d-6,1.5423789d-10,-4.6051132d-15,
34.92642d0
ibet(l,k), l=1,.,is, k=1,.,ir:
0 2 0 0 0 0 0 0
0 1 0 0 1 0 0 0
0 1 1 0 0 0 0 0
0 1 0 1 0 0 0 0
0 1 0 0 0 1 0 0
0 1 0 0 0 0 1 0
0 0 2 0 0 0 0 0
0 0 1 0 0 1 0 0
0 1 1 0 0 0 0 0
0 0 1 1 0 0 0 0
0 0 1 0 1 0 0 0
0 0 1 0 0 0 1 0
0 1 0 0 0 0 1 0
0 0 1 0 0 0 1 0
0 0 0 1 0 0 1 0
0 0 0 0 1 0 1 0
0 0 0 0 0 1 1 0
0 0 0 0 0 0 2 0
0 0 1 0 1 0 0 0
0 1 0 0 0 1 0 0
0 1 1 0 0 0 0 0
1 0 0 0 0 0 0 1
irnp(l,k), l=1,.,is, k=1,.,ir:
0 1 0 0 2 0 0 0
0 0 0 0 3 0 0 0
0 0 1 0 2 0 0 0
0 0 0 1 2 0 0 0
0 0 0 0 2 1 0 0
0 0 0 0 2 0 1 0
```

```
0 0 1 0 0 2 0 0
0 0 0 0 0 3 0 0
0 1 0 0 0 2 0 0
0 0 0 1 0 2 0 0
0 0 0 0 1 2 0 0
0 0 0 0 0 2 1 0
0 1 0 0 1 1 0 0
0 0 1 0 1 1 0 0
0 0 0 1 1 1 0 0
0 0 0 0 2 1 0 0
0 0 0 0 1 2 0 0
0 0 0 0 1 1 1 0
0 0 0 0 0 1 1 0
0 0 0 0 1 0 1 0
0 0 0 0 0 0 2 0
0 0 0 0 1 1 0 0
rk1(k), rk2(k), rk3(k), k=1,.,ir:
3.0000000e+15,-1.5,1.132942e5
1.4999999e+16,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
3.6000000e+15,-1.5,5.939902e4
2.0999999e+12,-0.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
1000000.0,0.5,3.625576e3
5.0000000e+07,0.0,3.802827e4
9.1000002e+18,-2.5,6.501867e4
1.8000000e+15,-1.5,0.0e0
ithb(k), k=1,.,ir:
1,1,1,1,1,1,2,2,2,2,2,2,3,3,3,3,3,3,0,0,0,0
```

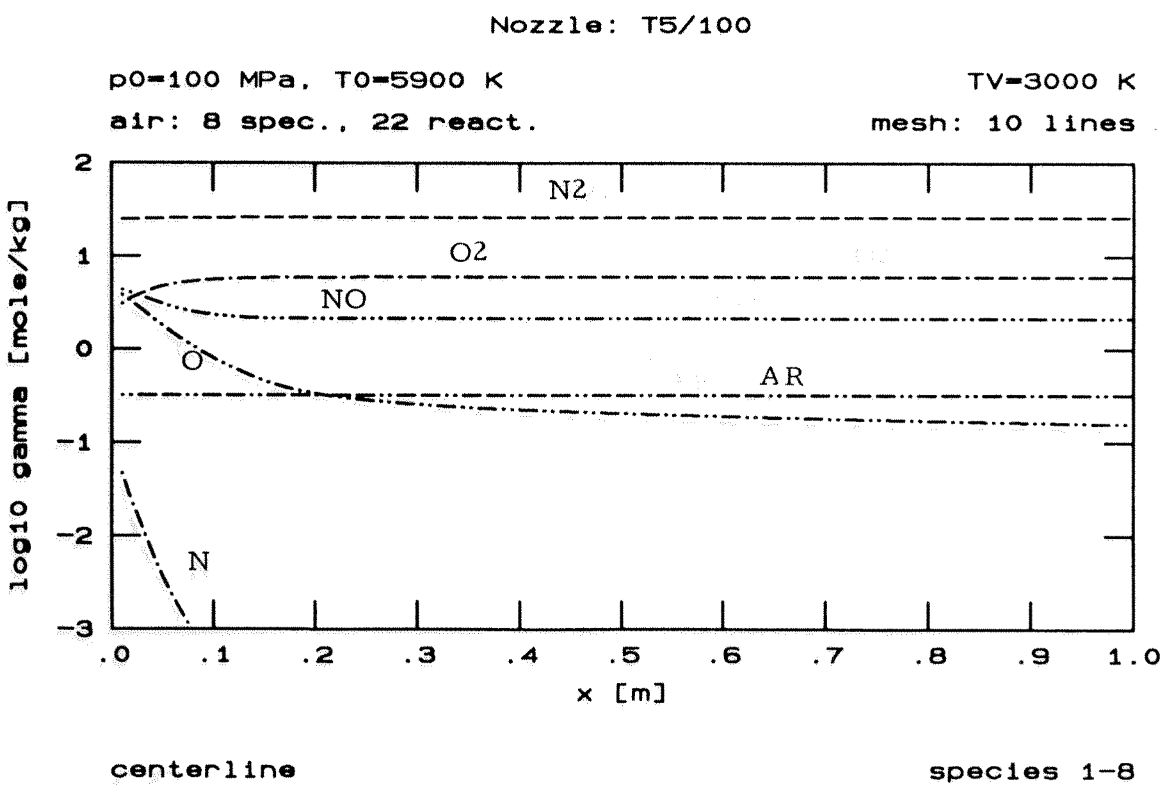
```
Nozzle: T5/100 (GALCIT)
expansion of air (8 species, 22 reactions)
--------------------------------------------------
JOBID =        2
--------------------------------------------------
name of output file 'outpt2':air2bres
--------------------------------------------------
to be calculated is/are:
                          two-dimensional nonequilibrium flow solution:
                             -switch parameter for switch from equilibrium
                              to nonequilibrium solution: dcrit= 0.1000E-01
                             -initial conditions via 1-D equilibrium flow
* choked flow *
* vibrational modes frozen for temperature  T < Tv=  0.3000E+04 K
upstream/downstream boundary of flow field: xu=0.1000E-01 m, xd=0.1000E+01 m
grid lines in xi/eta direction             : mmax= 150,  nmax=  10
--------------------------------------------------
reservoir temperature and pressure: T0 =  0.5900E+04 K, p0 =  0.1000E+09 Pa
--------------------------------------------------
number of independent/dependent species: ic=   4  is=   8
independent species and their mole fractions (in case that no other species
are present):
              E-        0.0000E+00
              N2        0.7811E+00
              O2        0.2095E+00
              AR        0.9340E-02
--------------------------------------------------
dependent species:
              N
              O
              NO
              NO+
--------------------------------------------------
g0(i), i=1,...,ic, [mol/kg] (concentrations of independent species
  (when only independent species are present)):
  0.0000E+00  0.2697E+02  0.7235E+01  0.3225E+00
g0(j), j=ic+1,...,is, [mol/kg] (absolute maximum concentrations of
  dependent species):
  0.5394E+02  0.1447E+02  0.1447E+02  0.1447E+02
--------------------------------------------------
equilibrium reservoir state:
T0 =   0.5900E+04 K,    p0 =   0.1000E+09 Pa, rho0 =   0.5478E+02 kg/m**3
h0 =   0.9223E+07 J/kg, s0 =   0.8823E+04 J/(kgK)
species concentrations [mol/kg] (reservoir):
  0.8928E-03  0.2437E+02  0.2144E+01  0.3225E+00  0.1908E+00  0.5173E+01
  0.5009E+01  0.8928E-03
--------------------------------------------------
two-dimensional nozzle flow solution: choked flow
initial conditions at xu =   0.100000E-01m (area =   0.115597E+01)
   n          u [m/s]     v [m/s]     p [Pa]      rho [kg/m**3]
  g(j), j= ic+1,...,is [mol/kg]
   1          0.1896E+04  0.0000E+00  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   2          0.1896E+04  0.4673E+02  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   3          0.1894E+04  0.9338E+02  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   4          0.1891E+04  0.1399E+03  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   5          0.1887E+04  0.1861E+03  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   6          0.1882E+04  0.2320E+03  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   7          0.1876E+04  0.2774E+03  0.3313E+08  0.2211E+02
```

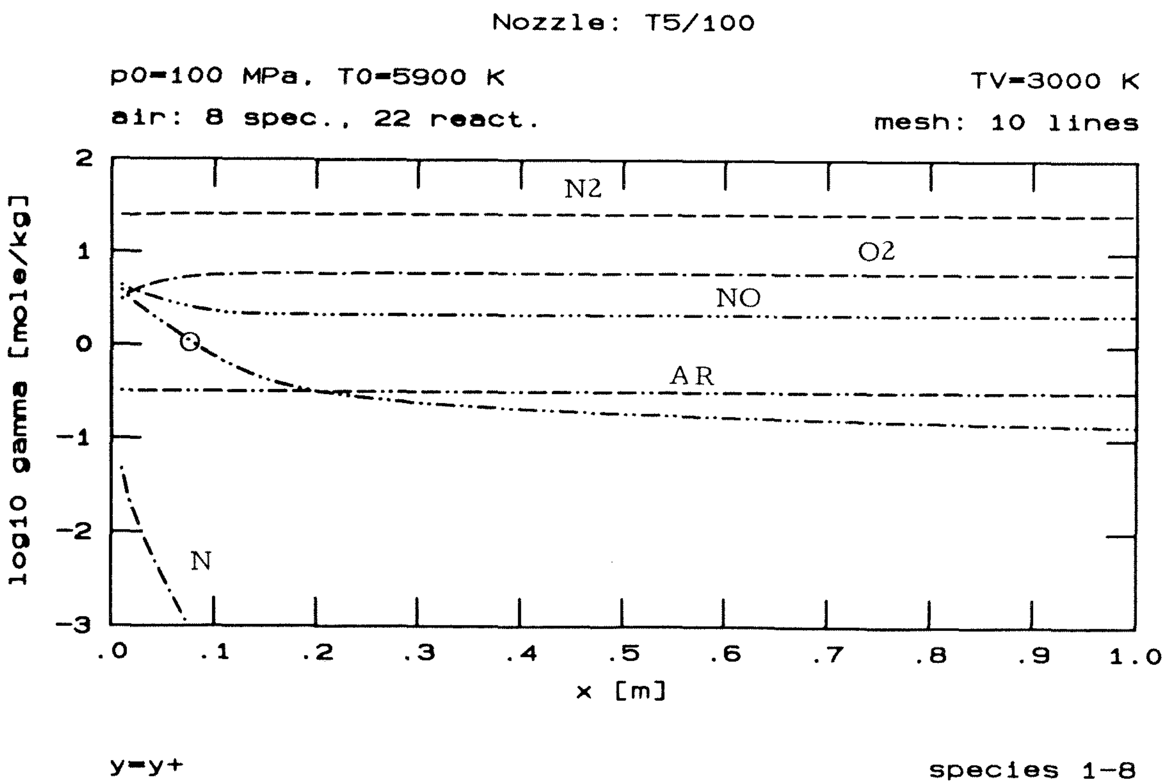
```
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   8          0.1868E+04  0.3224E+03  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
   9          0.1860E+04  0.3669E+03  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
  10          0.1851E+04  0.4107E+03  0.3313E+08  0.2211E+02
  0.4737E-01  0.3892E+01  0.4417E+01  0.2007E-03
..................................................
***
*** fully nonequilibrium flow calculation starts right at the
*** upstream boundary (at x=xu)
***
solution at xd =    0.100000E+01 m (area =    0.109644E+03)
   n          u [m/s]     v [m/s]     p [Pa]      rho [kg/m**3]
  g(j), j= ic+1,...,is [mol/kg]
   1          0.3869E+04  0.0000E+00  0.2837E+05  0.9700E-01
  0.1053E-08  0.1577E+00  0.2151E+01  0.4278E-06
   2          0.3868E+04  0.5360E+01  0.2862E+05  0.9762E-01
  0.1071E-08  0.1574E+00  0.2151E+01  0.4271E-06
   3          0.3866E+04  0.1276E+02  0.2934E+05  0.9936E-01
  0.1127E-08  0.1567E+00  0.2152E+01  0.4251E-06
   4          0.3863E+04  0.2356E+02  0.3052E+05  0.1022E+00
  0.1236E-08  0.1556E+00  0.2153E+01  0.4218E-06
   5          0.3859E+04  0.3858E+02  0.3215E+05  0.1061E+00
  0.1422E-08  0.1540E+00  0.2155E+01  0.4175E-06
   6          0.3854E+04  0.5790E+02  0.3421E+05  0.1109E+00
  0.1718E-08  0.1520E+00  0.2156E+01  0.4122E-06
   7          0.3848E+04  0.8086E+02  0.3671E+05  0.1166E+00
  0.2175E-08  0.1495E+00  0.2157E+01  0.4059E-06
   8          0.3841E+04  0.1060E+03  0.3969E+05  0.1233E+00
  0.2880E-08  0.1467E+00  0.2158E+01  0.3989E-06
   9          0.3833E+04  0.1307E+03  0.4336E+05  0.1313E+00
  0.4007E-08  0.1434E+00  0.2158E+01  0.3911E-06
  10          0.3824E+04  0.1509E+03  0.4817E+05  0.1416E+00
  0.5976E-08  0.1397E+00  0.2157E+01  0.3826E-06
--------------------------------------------------
```

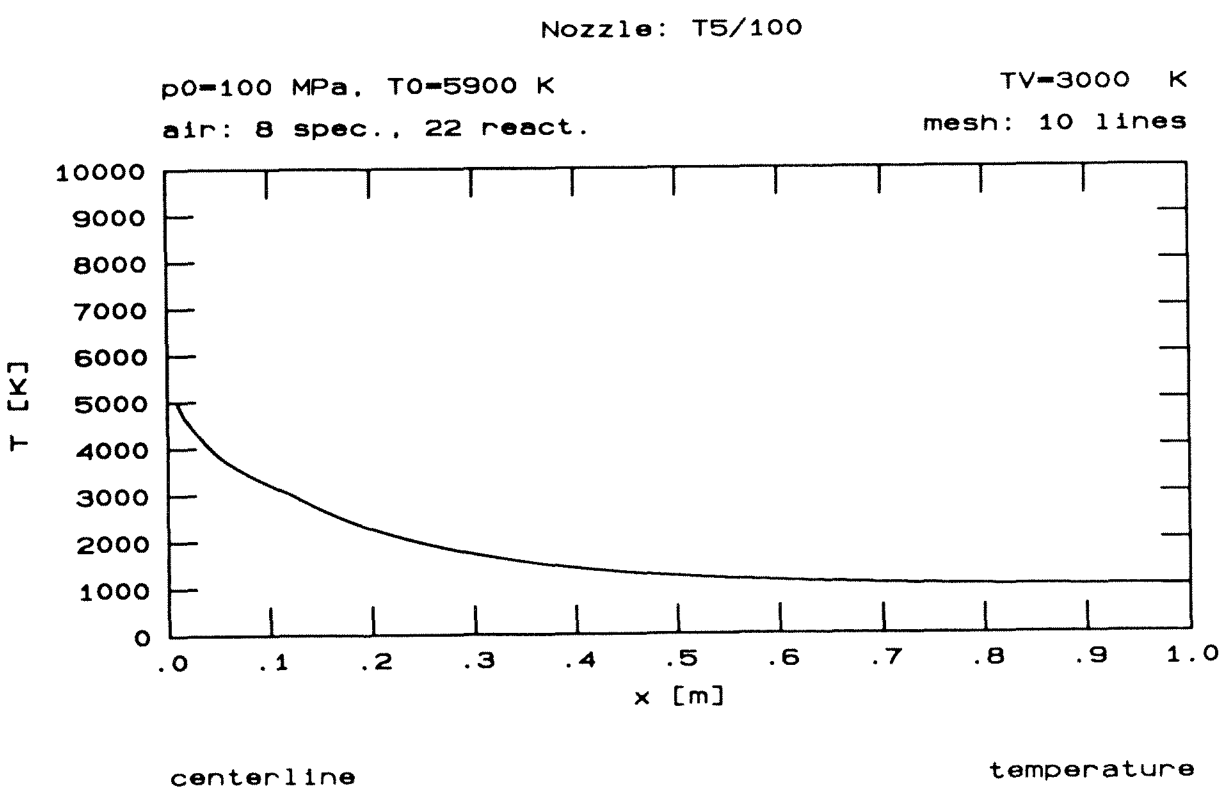
```
Nozzle: T5/100 (GALCIT)
expansion of air (8 species, 22 reactions)
names of output data files
air3bsum
air3bres
job id. no.,iequil,ifrzn,i2d,iout
3,0,0,1,0
xu,xd,mmax,nmax
0.005,1.0,200,10
T0,P0
7260.0,100.0e+06
Tv
3.0d3
ichkd,rminlt
1,2.0
dcrit
1.0d-2
ic,is,ir
4,8,22
indep. species: symb(i), g0(i), i=1,.,ic
 E- ,0.0d0
 N2 ,0.78112d0
 O2 ,0.20954d0
 AR ,0.00934d0
alph(j,i), j=ic+1,.,is, i=1,.,ic
0.0,0.5,0.0,0.0
0.0,0.0,0.5,0.0
0.0,0.5,0.5,0.0
-1.0,0.5,0.5,0.0
thermodynamic properties of (is) species:
 E-
5.4847d-7,1,0.0e0,5.0d3
1.0,1.0,1,0
2.0
0.0e0
0.0e0
20.78675d0,0.0d0,0.0d0,0.0d0,0.0d0,
-97.57301d0
 N2
28.0160d-3,2,0.0e0,5.0d3
2.86,2.0,4,1
1.0,3.0,6.0,1.0
0.0e0,72352.91,85843.07,88323.06
3353.24
28.69805d0,5.1357108d-3,-1.0604805d-6,9.1105665d-11,-2.27333721d-15,
25.53668d0
 O2
32.0d-3,2,0.0e0,5.0d3
2.07,2.0,5,1
3.0,2.0,1.0,3.0,3.0
0.0e0,11096.78,18996.51,51965.59,71700.80
2238.97
27.01839d0,8.253918d-3,-1.6716921d-6,1.4778012d-10,-4.1585184d-15,
49.18163
 AR
39.944d-3,1,0.0e0,5.0d3
1.0,1.0,3,0
1.0,5.0,3.0
0.0e0,134099.5,134973.2
0.0e0
21.31292d0,-5.9728982d-4,1.8631269d-7,-2.2439826d-11,9.2875987d-16,
33.26661d0
 N
14.008d-3,1,471243.3268,5.0d3
```

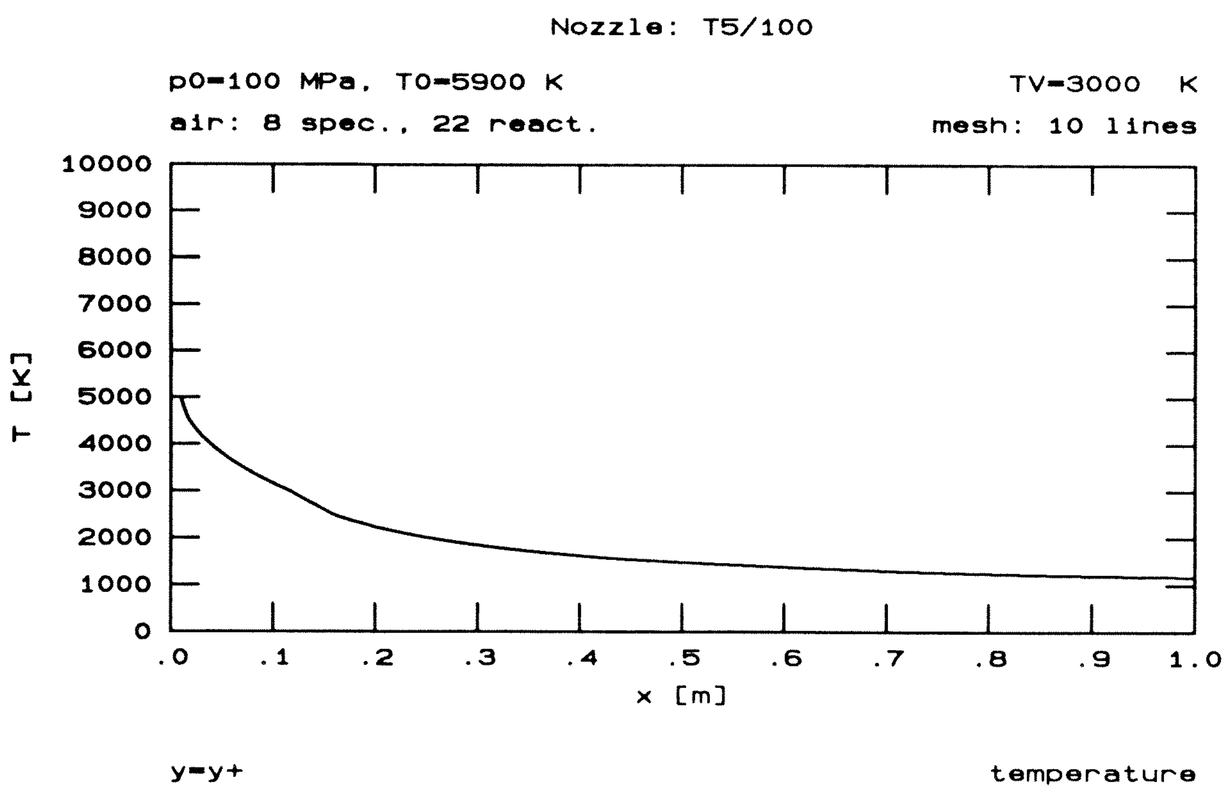
```
1.0,1.0,5,0
4.0,6.0,4.0,6.0,12.0
0.0e0,27682.28,27758.32,41520.40,119951.2
0.0e0
25.01829,-5.212693d-3,1.574425d-6,-1.3852965d-10,3.880839d-15,
10.83801d0
 O
16.0d-3,1,246857.841,5.0d3
1.0,1.0,6,0
5.0,3.0,1.0,5.0,1.0
5.0
0.0e0,228.9249,326.7953,22845.16,48650.7
106202.7
0.0e0
21.56952d0,-8.3295238d-4,2.99205d-7,-2.8873997d-11,8.9304039d-16,
38.25274d0
 NO
30.008d-3,2,89890.90965,5.0d3
2.42,1.0,3,1
4.0,2.0,4.0
0.0e0,63296.52,66107.84
2699.18
31.23181d0,3.4655021d-3,-6.5841147d-7,5.6218415d-11,-1.5014366d-15,
30.02577d0
 NO+
30.00765d-3,2,984961.9485,5.0d3
2.42,1.0,6,1
1.0,6.0,3.0,6.0,2.0
0.0e0
0.0e0,58025.33,85093.78,105107.5,105539.5
0.0e0
3372.95
28.24824d0,6.2350007d-3,-1.512119d-6,1.5423789d-10,-4.6051132d-15,
34.92642d0
ibet(l,k), l=1,.,is, k=1,.,ir:
0 2 0 0 0 0 0 0
0 1 0 0 1 0 0 0
0 1 1 0 0 0 0 0
0 1 0 1 0 0 0 0
0 1 0 0 0 1 0 0
0 1 0 0 0 0 1 0
0 0 2 0 0 0 0 0
0 0 1 0 0 1 0 0
0 1 1 0 0 0 0 0
0 0 1 1 0 0 0 0
0 0 1 0 1 0 0 0
0 0 1 0 0 0 1 0
0 1 0 0 0 0 1 0
0 0 1 0 0 0 1 0
0 0 0 1 0 0 1 0
0 0 0 0 1 0 1 0
0 0 0 0 0 1 1 0
0 0 0 0 0 0 2 0
0 0 1 0 1 0 0 0
0 1 0 0 0 1 0 0
0 1 1 0 0 0 0 0
1 0 0 0 0 0 0 1
irnp(l,k), l=1,.,is, k=1,.,ir:
0 1 0 0 2 0 0 0
0 0 0 0 3 0 0 0
0 0 1 0 2 0 0 0
0 0 0 1 2 0 0 0
0 0 0 0 2 1 0 0
0 0 0 0 2 0 1 0
```

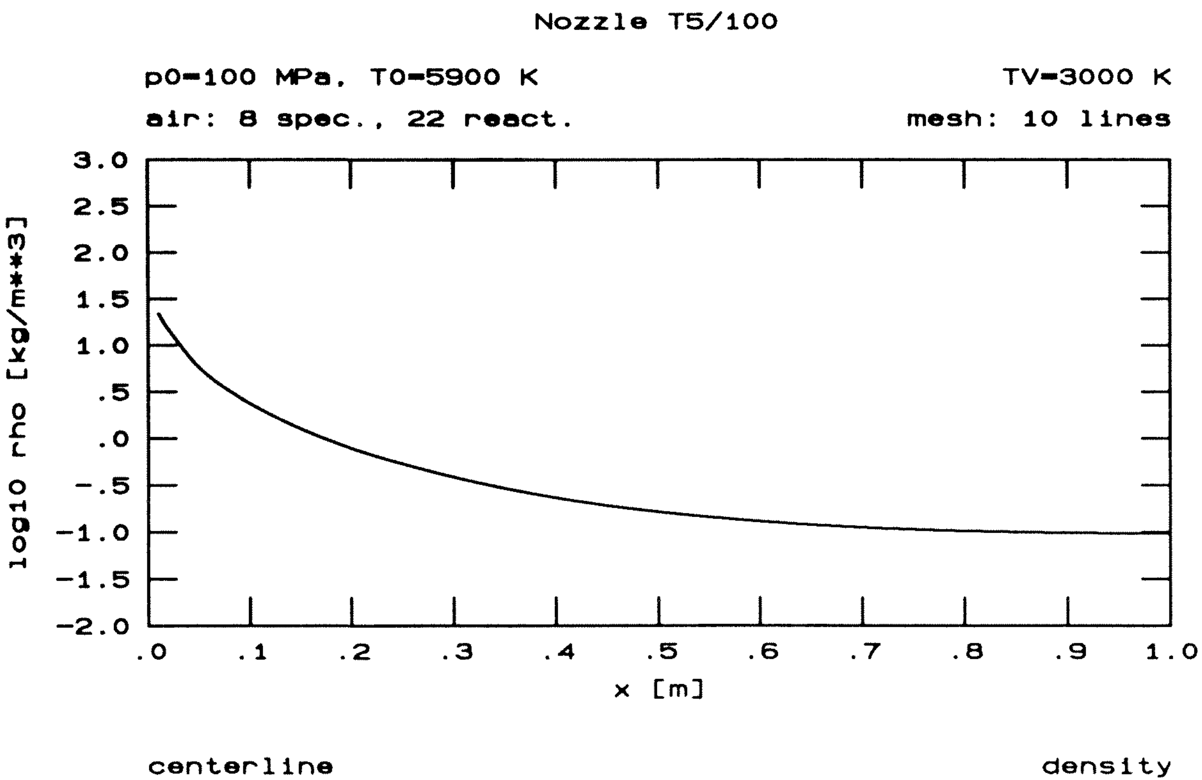
```
0 0 1 0 0 2 0 0
0 0 0 0 0 3 0 0
0 1 0 0 0 2 0 0
0 0 0 1 0 2 0 0
0 0 0 0 1 2 0 0
0 0 0 0 0 2 1 0
0 1 0 0 1 1 0 0
0 0 1 0 1 1 0 0
0 0 0 1 1 1 0 0
0 0 0 0 2 1 0 0
0 0 0 0 1 2 0 0
0 0 0 0 1 1 1 0
0 0 0 0 0 1 1 0
0 0 0 0 1 0 1 0
0 0 0 0 0 0 2 0
0 0 0 0 1 1 0 0
rk1(k), rk2(k), rk3(k), k=1,.,ir:
3.0000000e+15,-1.5,1.132942e5
1.4999999e+16,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
9.8999996e+14,-1.5,1.132942e5
3.6000000e+15,-1.5,5.939902e4
2.0999999e+12,-0.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
1.2000000e+15,-1.5,5.939902e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
5.2000000e+15,-1.5,7.551270e4
1000000.0,0.5,3.625576e3
5.0000000e+07,0.0,3.802827e4
9.1000002e+18,-2.5,6.501867e4
1.8000000e+15,-1.5,0.0e0
ithb(k), k=1,.,ir:
1,1,1,1,1,1,2,2,2,2,2,2,3,3,3,3,3,3,0,0,0,0
```

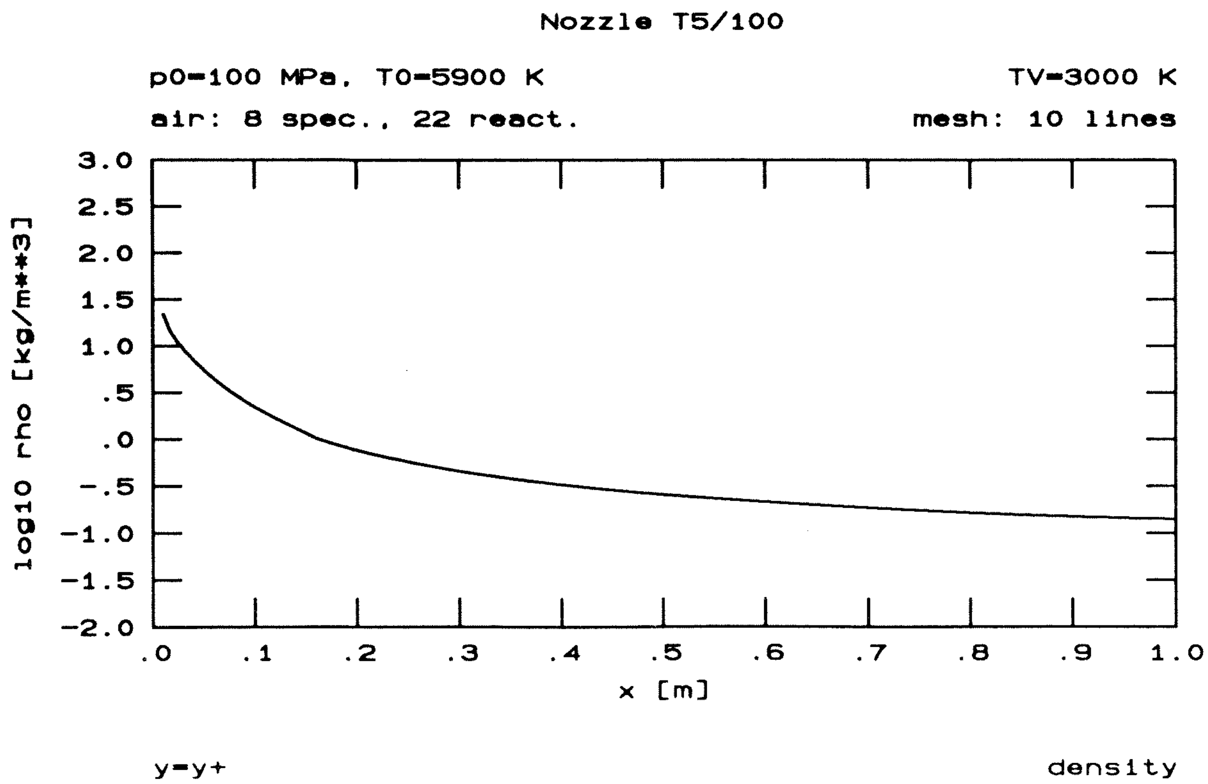

Nozzle: T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
N2
O2
NO
O
AR
N
log10 gamma [mole/kg]
2
1
0
-1
-2
-3
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
species 1-8

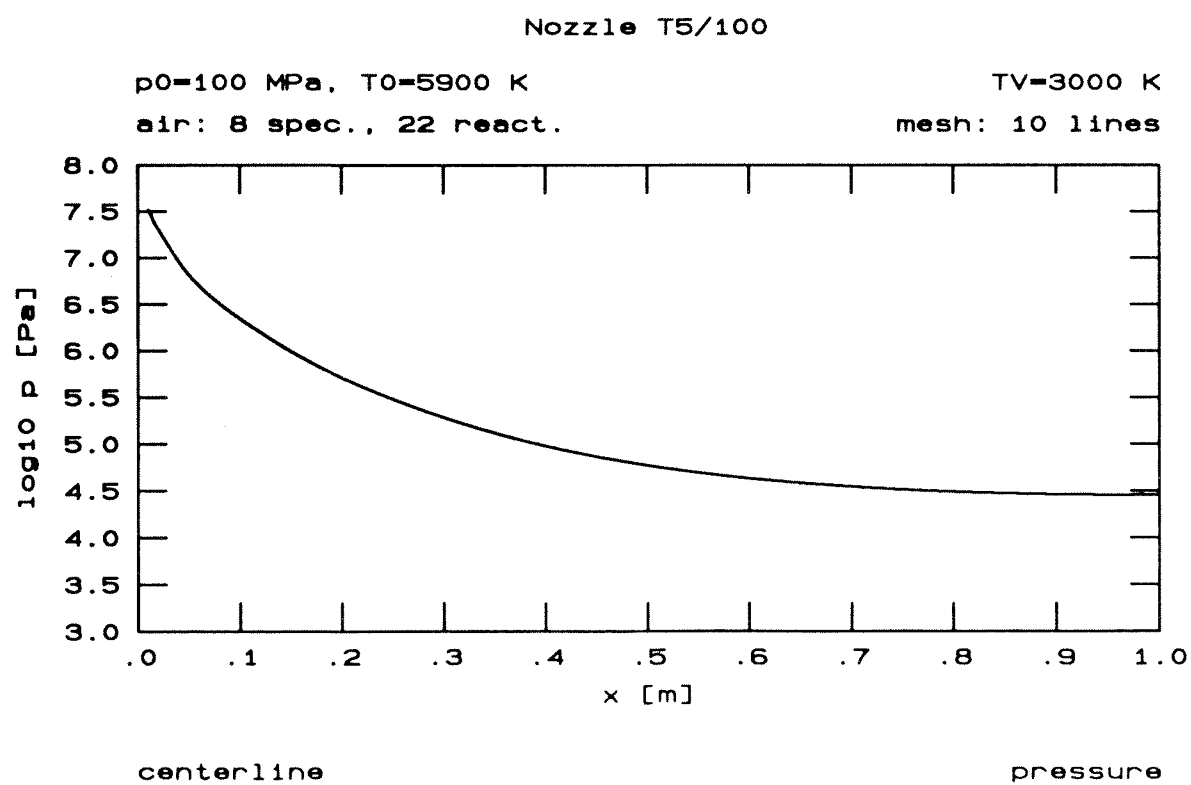

Nozzle: T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
N2
O2
NO
O
AR
N
2
1
0
-1
-2
-3
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
log10 gamma [mole/kg]
x [m]
y=y+
species 1-8

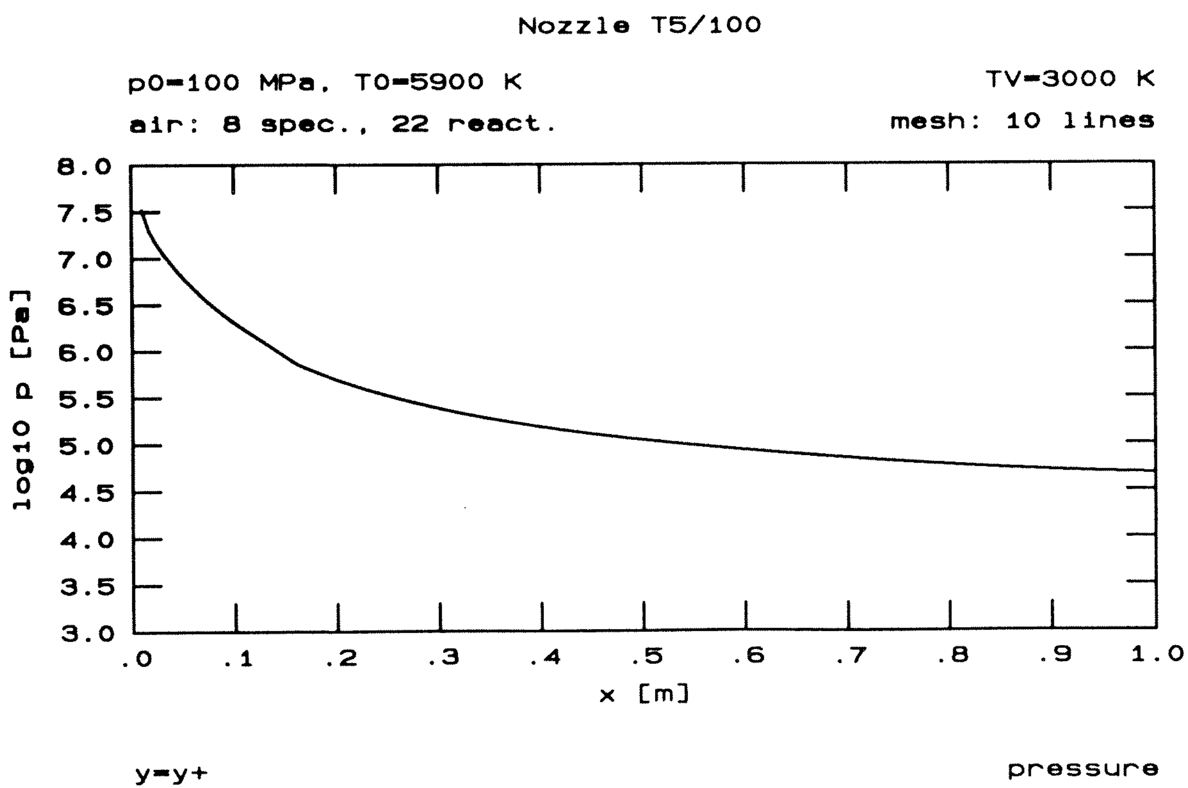

Nozzle: T5/100
p0=100 MPa, T0=5900 K
air: 8 spec., 22 react.
TV=3000 K
mesh: 10 lines
T [K]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
temperature

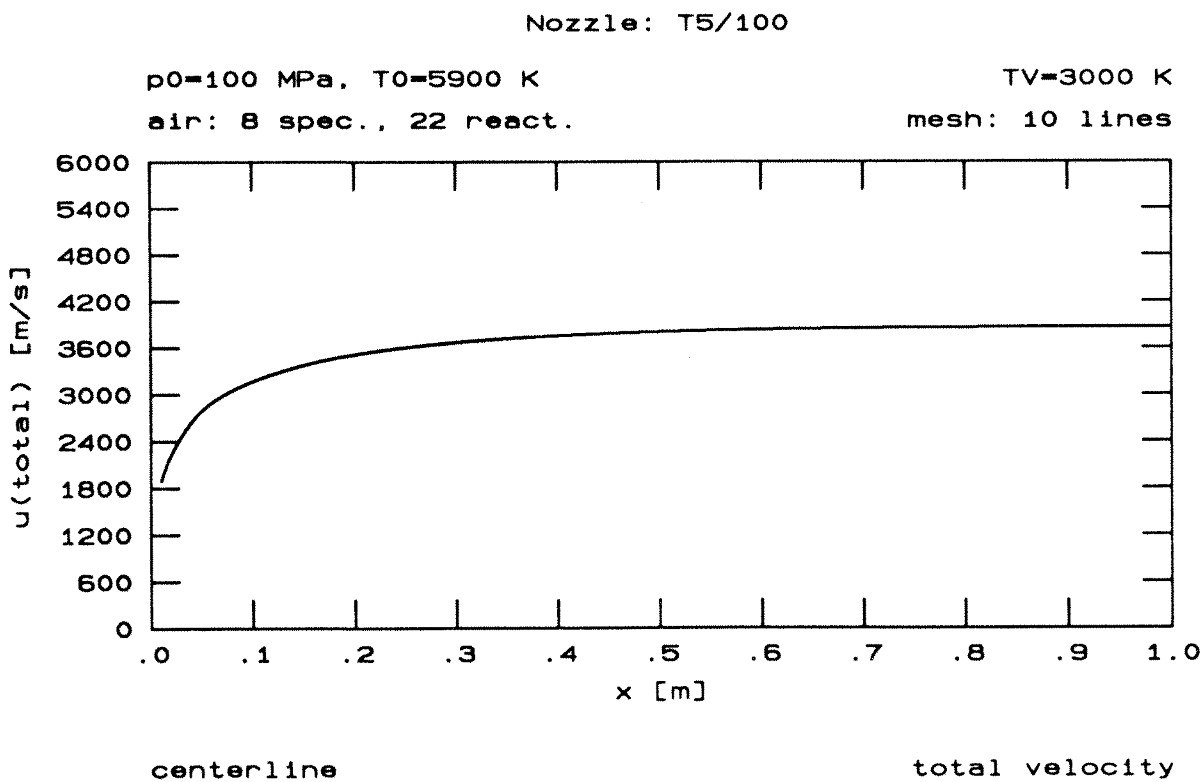

Nozzle: T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
T [K]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
temperature


Nozzle T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
3.0
2.5
2.0
1.5
1.0
.5
.0
-.5
-1.0
-1.5
-2.0
log10 rho [kg/m**3]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
density

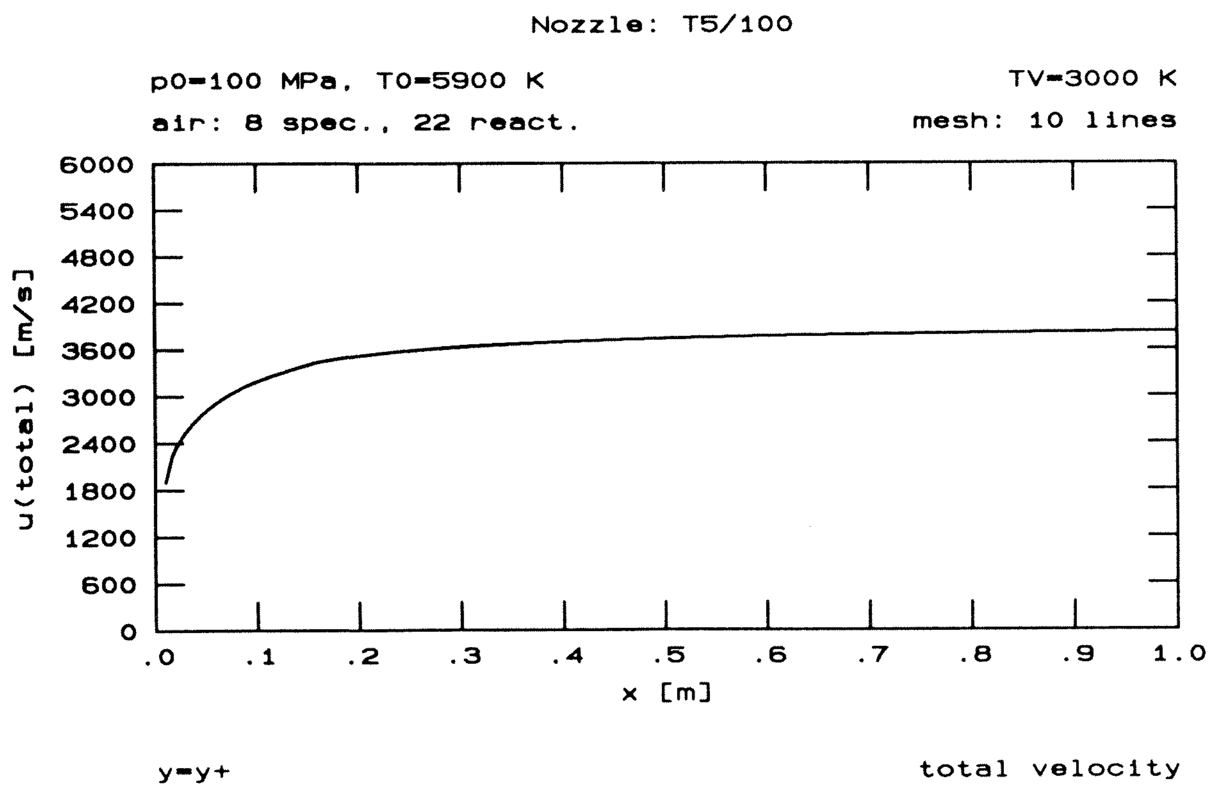

Nozzle T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 rho [kg/m**3]
3.0
2.5
2.0
1.5
1.0
.5
.0
-.5
-1.0
-1.5
-2.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
density


Nozzle T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 p [Pa]
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
pressure

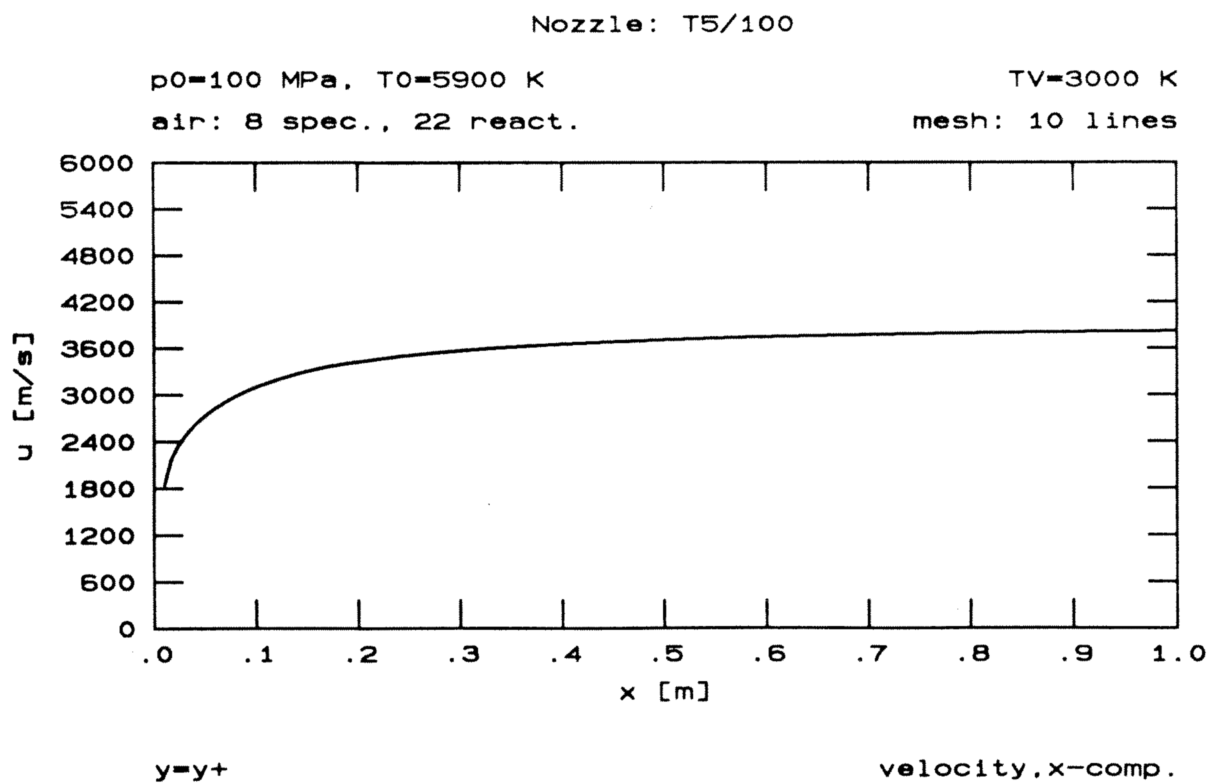

Nozzle T5/100
p0=100 MPa, T0=5900 K
air: 8 spec., 22 react.
TV=3000 K
mesh: 10 lines
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
log10 p [Pa]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
pressure



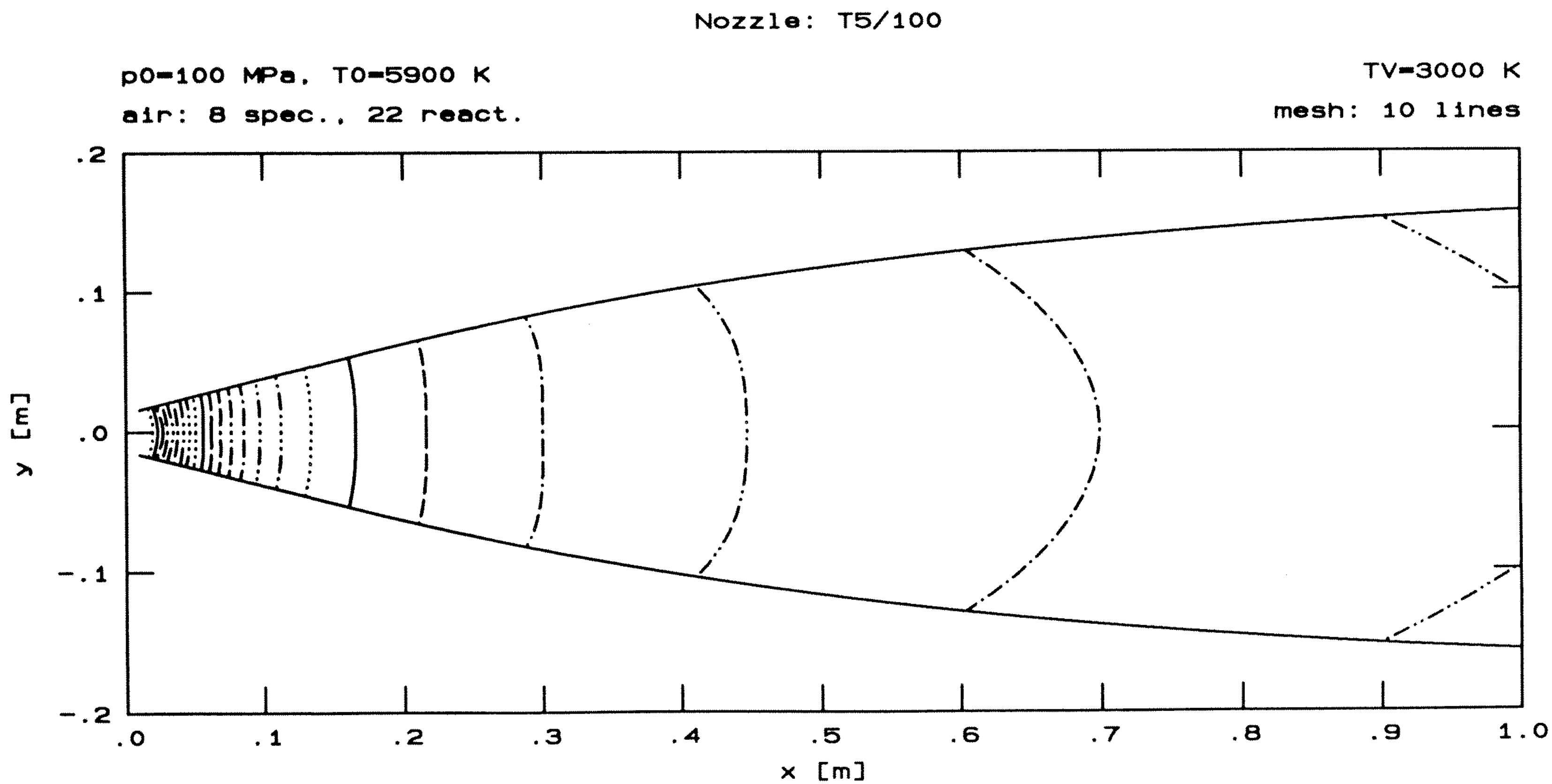
Nozzle: T5/100
p0=100 MPa, T0=5900 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
u(total) [m/s]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
total velocity



Nozzle: T5/100
p0=100 MPa, T0=5900 K
air: 8 spec., 22 react.
TV=3000 K
mesh: 10 lines
u(total) [m/s]
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
total velocity



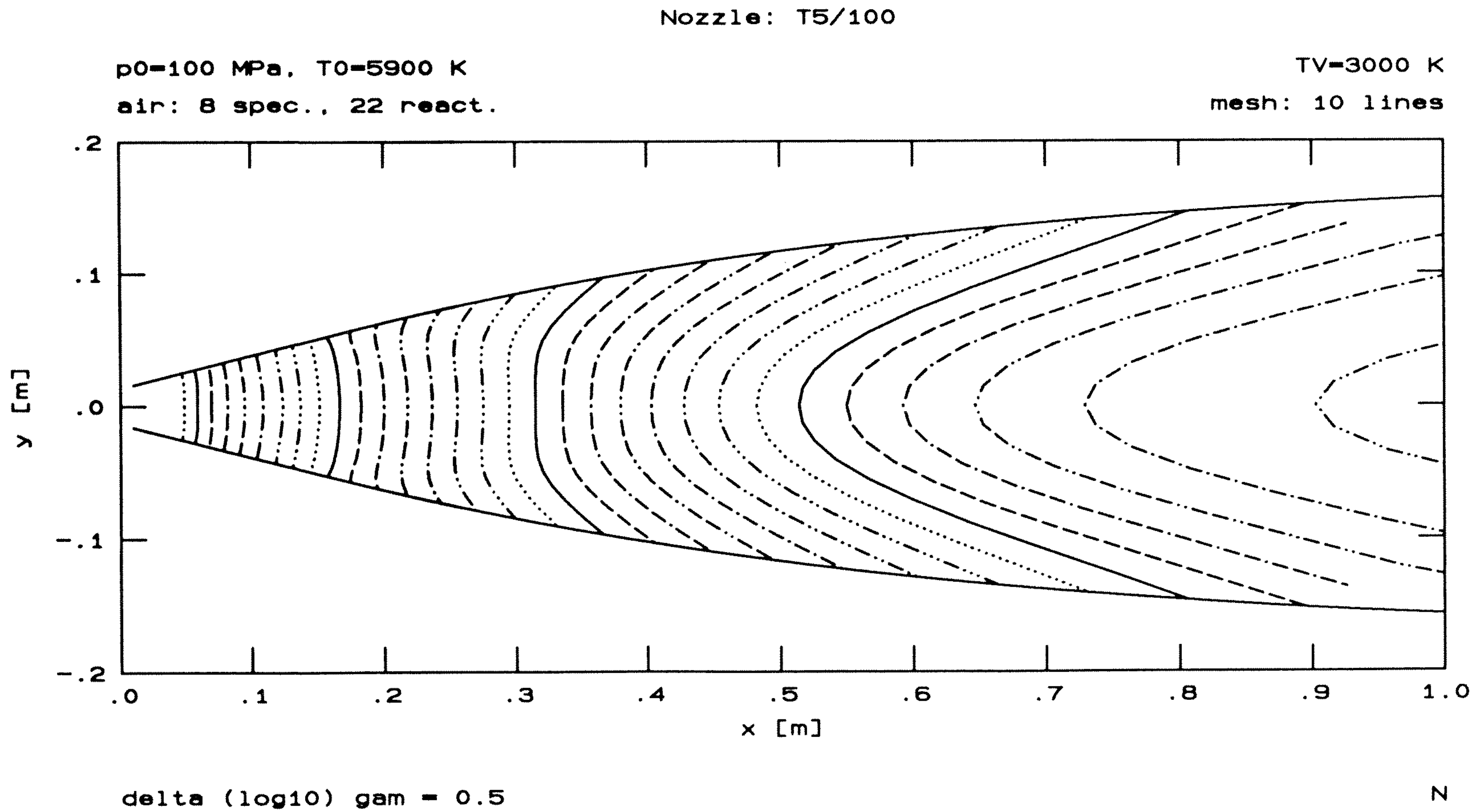
Nozzle: T5/100
p0=100 MPa, T0=5900 K
air: 8 spec., 22 react.
TV=3000 K
mesh: 10 lines
u [m/s]
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
velocity,x-comp.



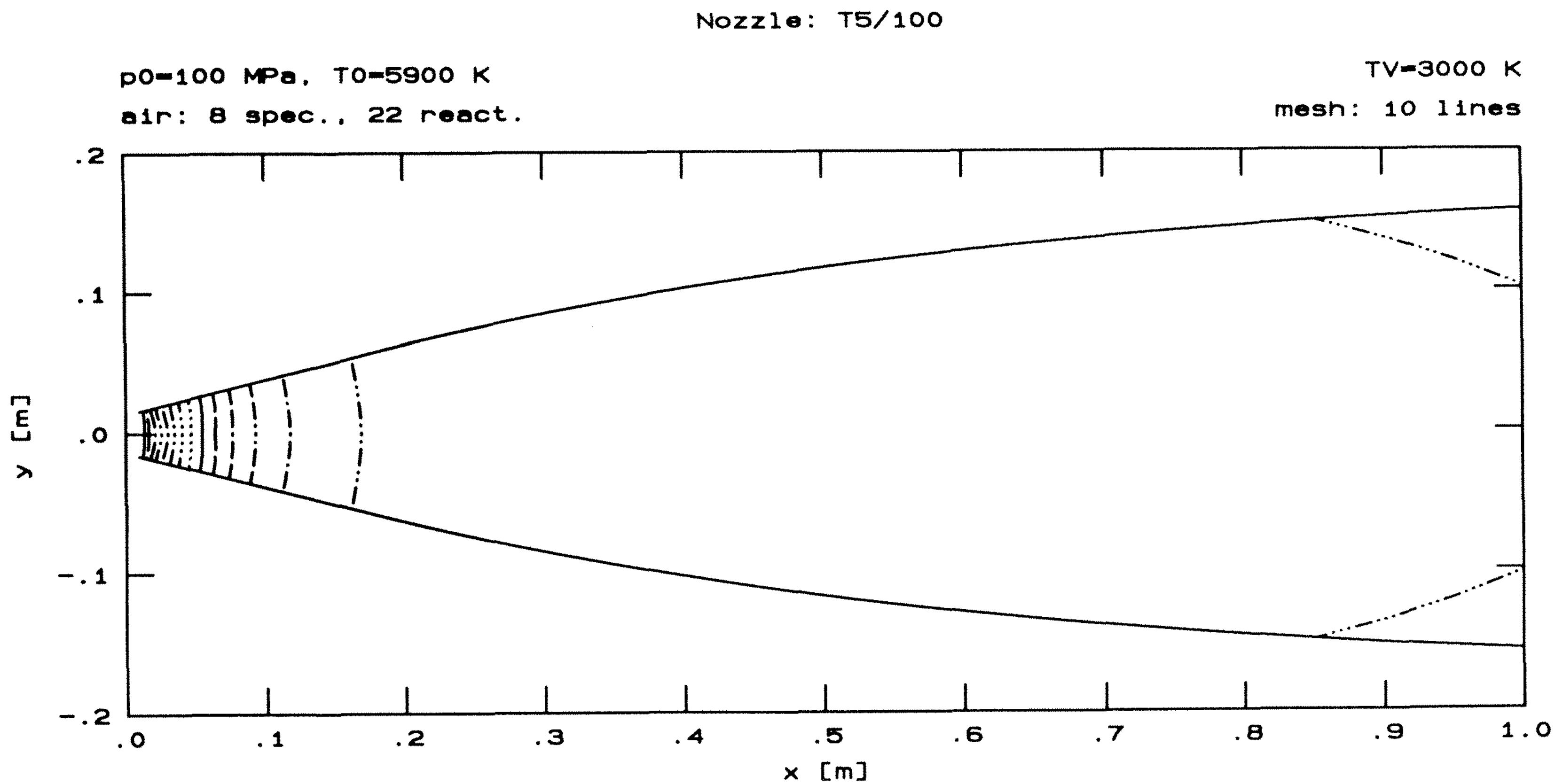
delta (log10) gam = 0.25

e-, NO+

First upstream contour line: $\gamma_{NO+} = 1.0 \times 10^{-4}$ mol/kg;
farthest downstream one: $\gamma_{NO+} = 4.09 \times 10^{-7}$ mol/kg.



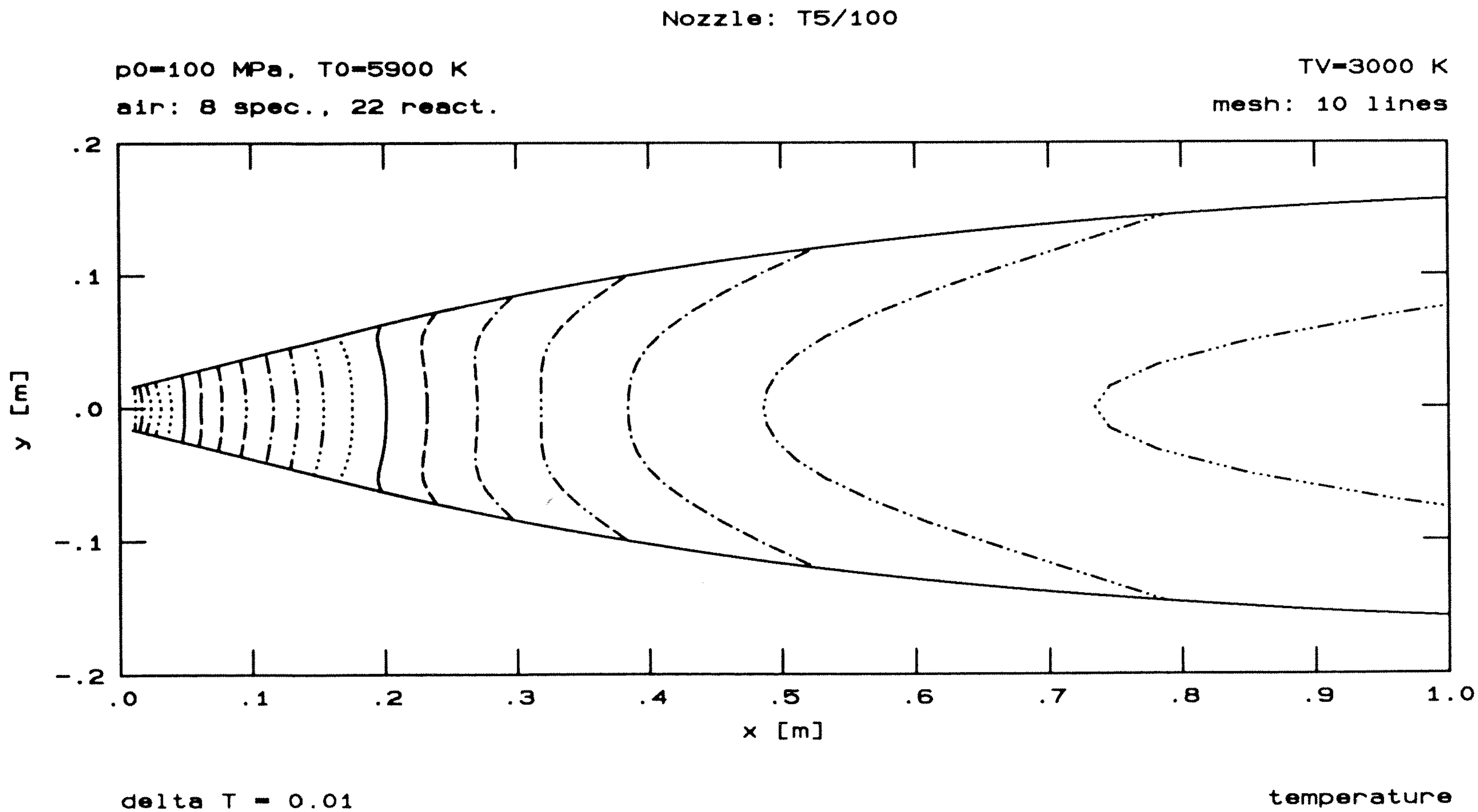
First upstream contour line: $\gamma_N = 3.9 \times 10^{-3}$ mol/kg;
farthest downstream one: $\gamma_N = 1.2 \times 10^{-9}$ mol/kg.



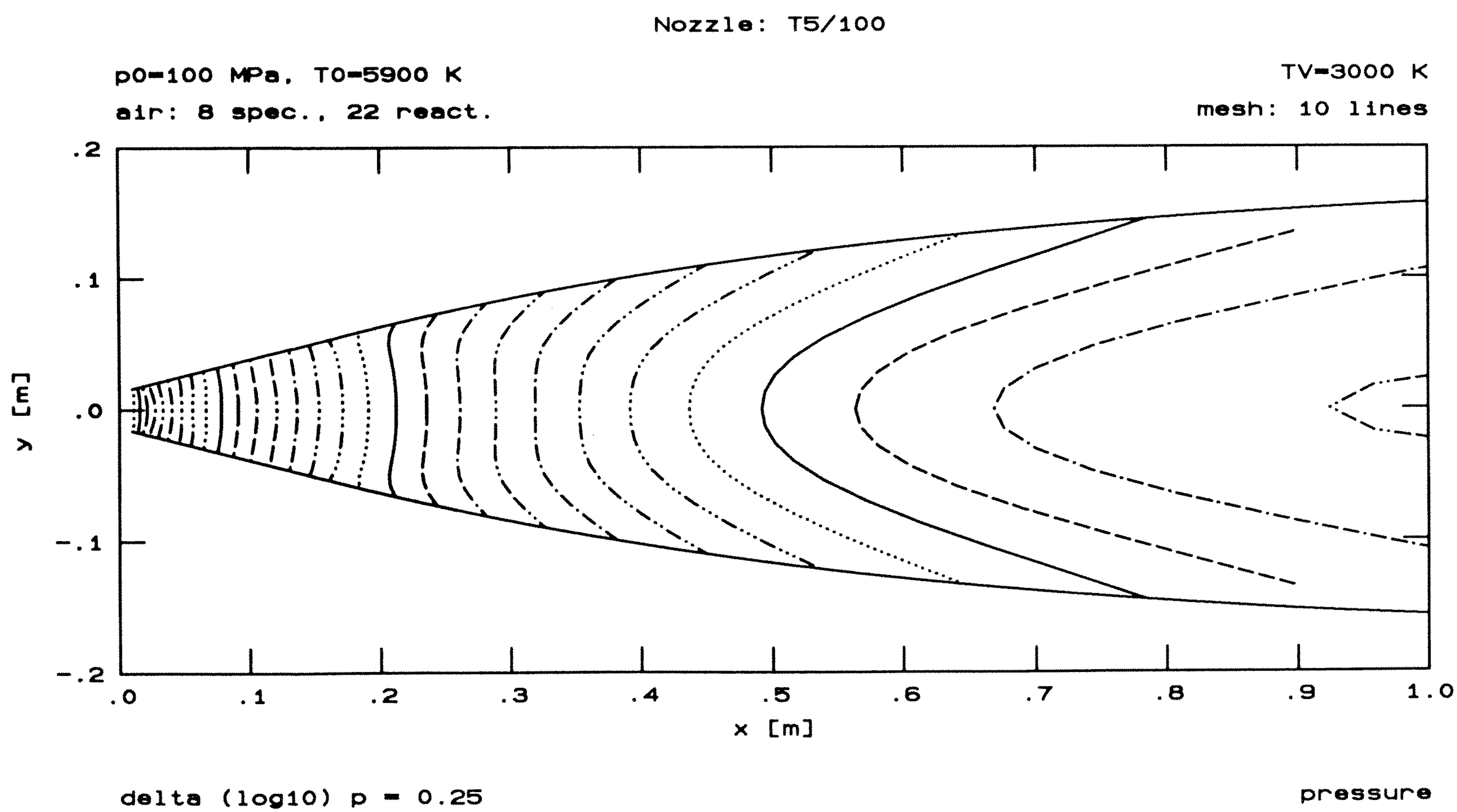
delta gam = 0.25

O

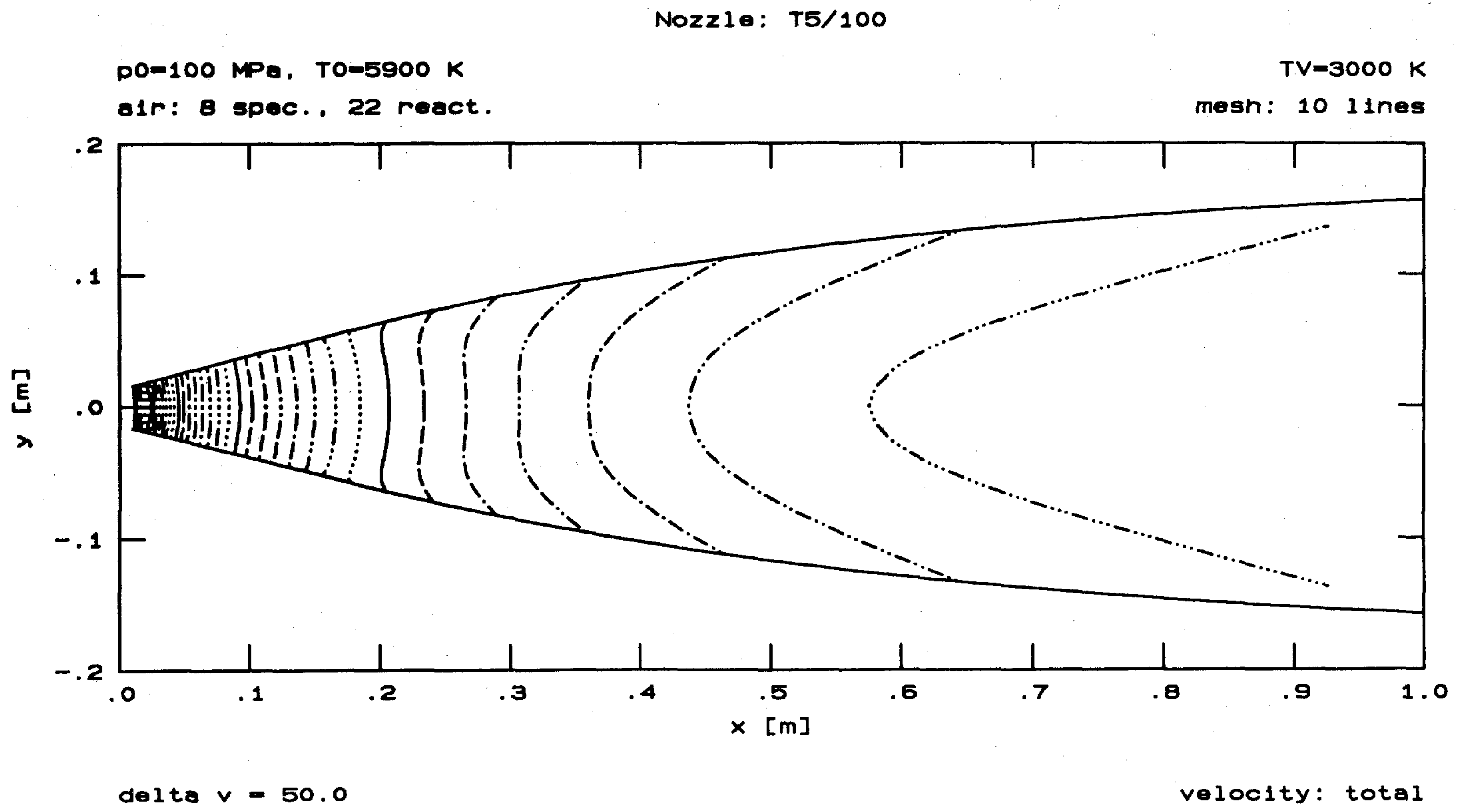
First upstream contour line: $\gamma_O = 3.65$ mol/kg;
farthest downstream one: $\gamma_O = 0.15$ mol/kg.



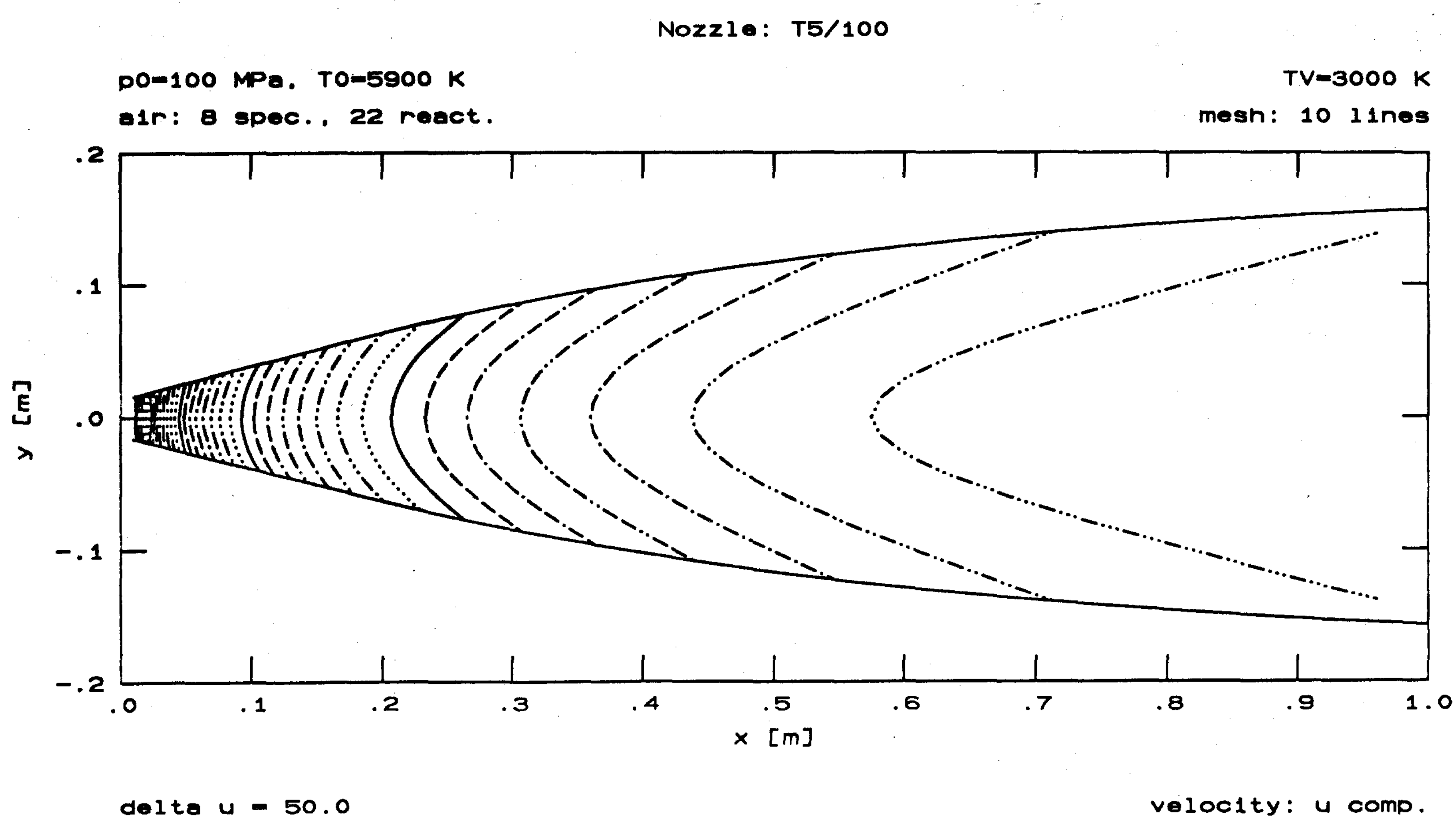
First upstream contour line: T = 4860 K;
farthest downstream one: T = 1060 K.



First upstream contour line: p = 3.165 x 10^7 Pa;
farthest downstream one: p = 28861.06 Pa.



First upstream contour line: w = 1930 m/s;
farthest downstream one: w = 3830 m/s.



First upstream contour line: u = 1930 m/s;
farthest downstream one: u = 3830 m/s.

```
Nozzle: T5/100 (GALCIT)
expansion of air (8 species, 22 reactions)
--------------------------------------------------
JOBID =        3
--------------------------------------------------
name of output file 'outpt2':air3bres
--------------------------------------------------
to be calculated is/are:
                          two-dimensional nonequilibrium flow solution:
                             -switch parameter for switch from equilibrium
                              to nonequilibrium solution: dcrit= 0.1000E-01
                             -initial conditions via 1-D equilibrium flow
* choked flow *
* vibrational modes frozen for temperature  T < Tv=  0.3000E+04 K
upstream/downstream boundary of flow field: xu=0.1000E-01 m, xd=0.1000E+01 m
grid lines in xi/eta direction             : mmax= 150,  nmax=  10
--------------------------------------------------
reservoir temperature and pressure: T0 =  0.7260E+04 K, p0 =  0.1000E+09 Pa
--------------------------------------------------
number of independent/dependent species: ic=   4  is=   8
independent species and their mole fractions (in case that no other species
are present):
              E-         0.0000E+00
              N2         0.7811E+00
              O2         0.2095E+00
              AR         0.9340E-02
--------------------------------------------------
dependent species:
              N
              O
              NO
              NO+
--------------------------------------------------
g0(i), i=1,...,ic, [mol/kg] (concentrations of independent species
  (when only independent species are present)):
  0.0000E+00  0.2697E+02  0.7235E+01  0.3225E+00
g0(j), j=ic+1,...,is, [mol/kg] (absolute maximum concentrations of
  dependent species):
  0.5394E+02  0.1447E+02  0.1447E+02  0.1447E+02
--------------------------------------------------
equilibrium reservoir state:
T0 =   0.7260E+04 K,    p0 =   0.1000E+09 Pa, rho0 =   0.4189E+02 kg/m**3
h0 =   0.1248E+08 J/kg, s0 =   0.9319E+04 J/(kgK)
species concentrations [mol/kg] (reservoir):
  0.5988E-02  0.2422E+02  0.7887E+00  0.3225E+00  0.1317E+01  0.8711E+01
  0.4175E+01  0.5988E-02
--------------------------------------------------
two-dimensional nozzle flow solution: choked flow
initial conditions at xu =   0.100000E-01m (area =   0.115597E+01)
   n          u [m/s]     v [m/s]      p [Pa]      rho [kg/m**3]
  g(j), j= ic+1,...,is [mol/kg]
   1          0.2221E+04  0.0000E+00  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   2          0.2221E+04  0.5475E+02  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   3          0.2219E+04  0.1094E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   4          0.2215E+04  0.1638E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   5          0.2211E+04  0.2180E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   6          0.2205E+04  0.2718E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   7          0.2197E+04  0.3250E+03  0.3165E+08  0.1651E+02
```

```
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   8          0.2189E+04  0.3777E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
   9          0.2179E+04  0.4298E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
  10          0.2169E+04  0.4812E+03  0.3165E+08  0.1651E+02
  0.3917E+00  0.7803E+01  0.4035E+01  0.1638E-02
.................................................
***
*** fully nonequilibrium flow calculation starts right at the
*** upstream boundary (at x=xu)
***
solution at xd =    0.100000E+01 m (area =    0.109644E+03)
   n          u [m/s]     v [m/s]     p [Pa]      rho [kg/m**3]
  g(j), j= ic+1,...,is [mol/kg]
   1          0.4433E+04  0.0000E+00  0.3801E+05  0.7887E-01
  0.3052E-05  0.1046E+01  0.2129E+01  0.1492E-05
   2          0.4432E+04  0.1113E+02  0.3819E+05  0.7913E-01
  0.3094E-05  0.1044E+01  0.2129E+01  0.1489E-05
   3          0.4431E+04  0.2357E+02  0.3872E+05  0.7989E-01
  0.3217E-05  0.1040E+01  0.2127E+01  0.1482E-05
   4          0.4428E+04  0.3833E+02  0.3961E+05  0.8117E-01
  0.3432E-05  0.1033E+01  0.2125E+01  0.1471E-05
   5          0.4425E+04  0.5619E+02  0.4090E+05  0.8299E-01
  0.3751E-05  0.1023E+01  0.2121E+01  0.1456E-05
   6          0.4421E+04  0.7748E+02  0.4259E+05  0.8538E-01
  0.4190E-05  0.1010E+01  0.2113E+01  0.1437E-05
   7          0.4415E+04  0.1018E+03  0.4474E+05  0.8837E-01
  0.4775E-05  0.9958E+00  0.2103E+01  0.1417E-05
   8          0.4409E+04  0.1278E+03  0.4744E+05  0.9208E-01
  0.5555E-05  0.9794E+00  0.2087E+01  0.1394E-05
   9          0.4401E+04  0.1529E+03  0.5090E+05  0.9676E-01
  0.6627E-05  0.9621E+00  0.2067E+01  0.1369E-05
  10          0.4391E+04  0.1733E+03  0.5554E+05  0.1029E+00
  0.8206E-05  0.9449E+00  0.2043E+01  0.1343E-05
-------------------------------------------------
```

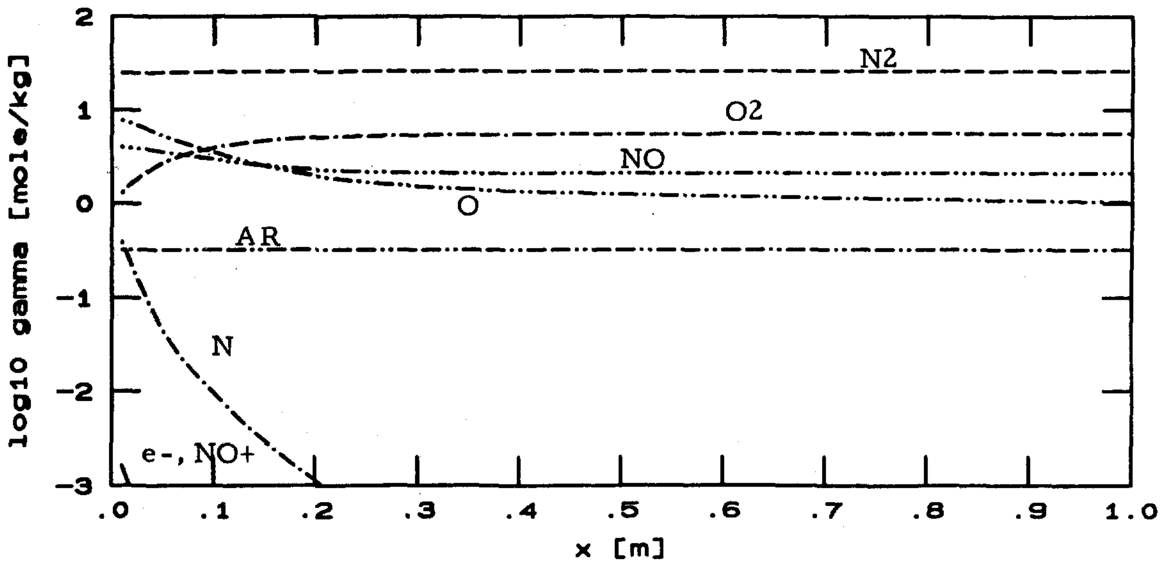
Nozzle: T5/100

p0=100 MPa, T0=7260 K

TV=3000 K

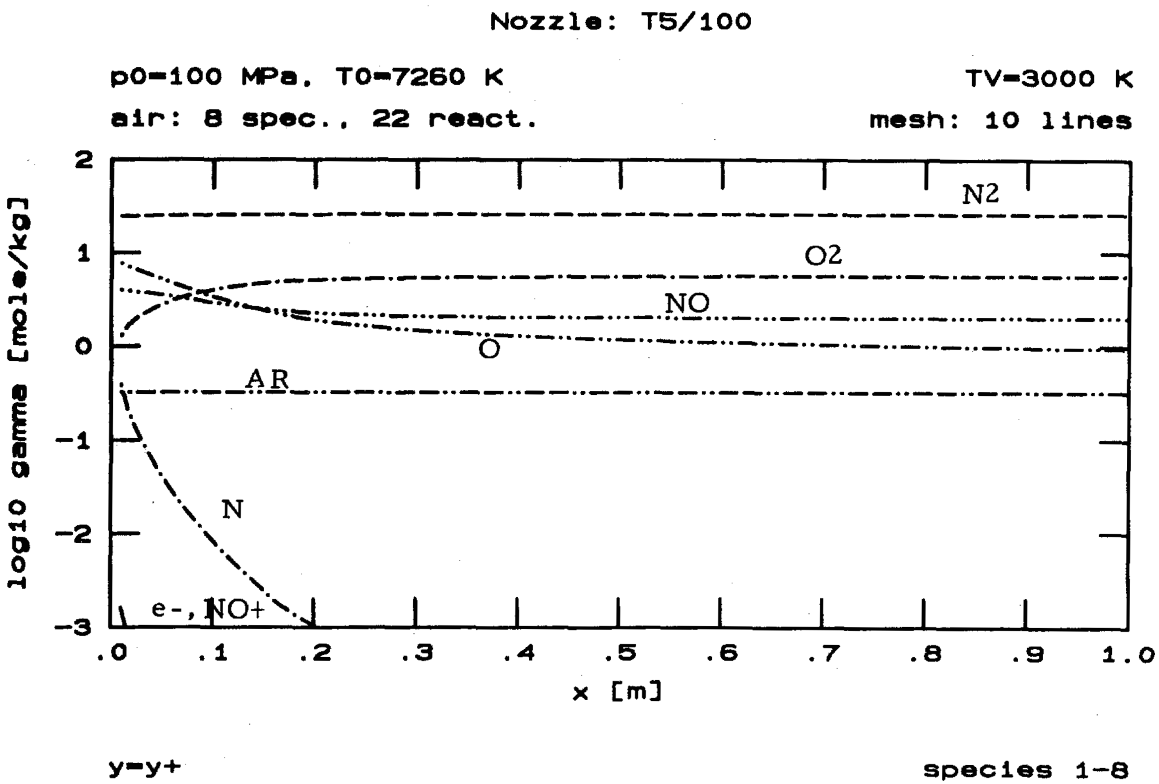
air: 8 spec., 22 react.

mesh: 10 lines



centerline

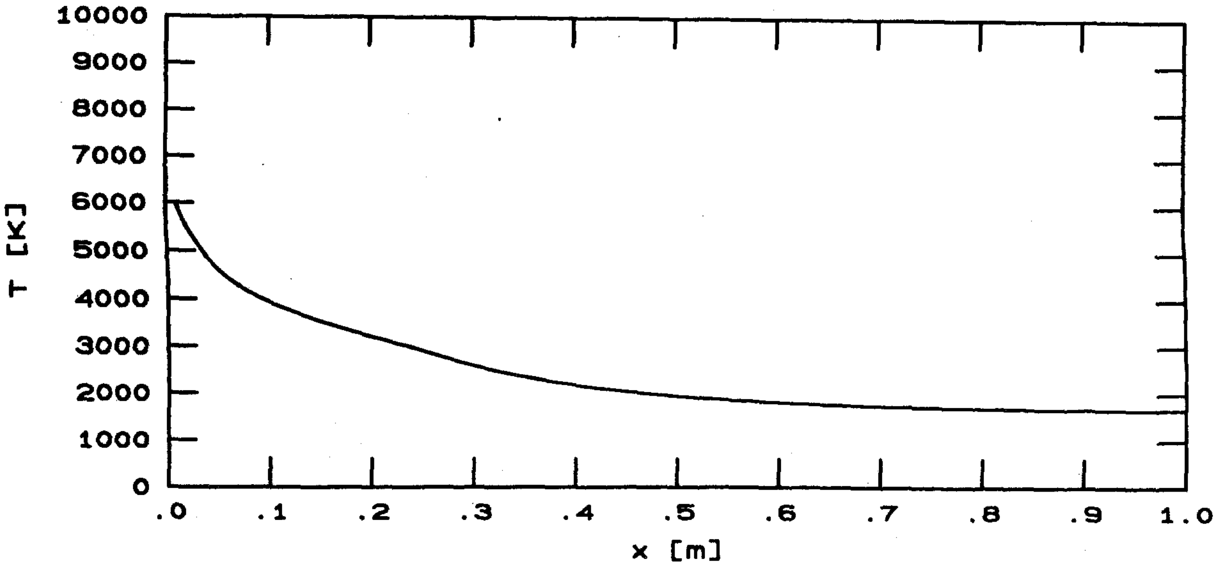
species 1-8


Nozzle: T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 gamma [mole/kg]
N2
O2
NO
O
AR
N
e-, NO+
x [m]
y=y+
species 1-8

Nozzle: T5/100

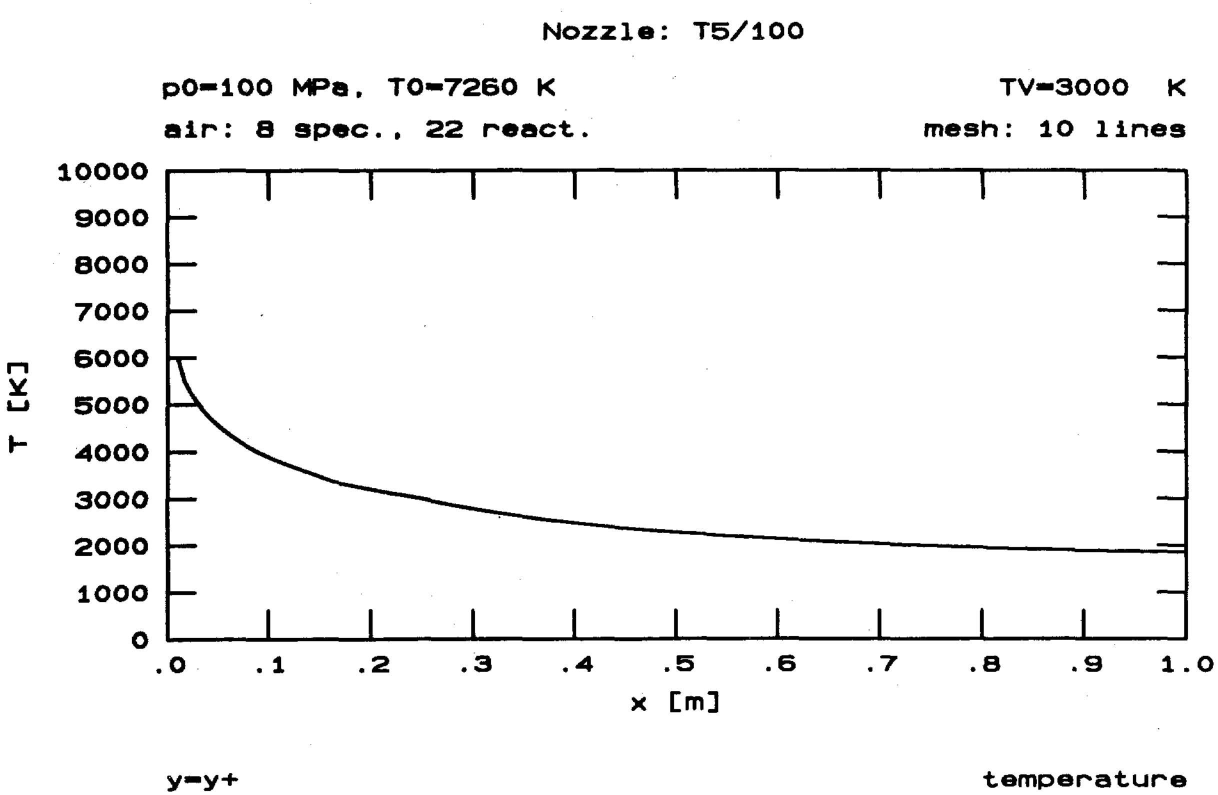
p0=100 MPa, T0=7260 K
air: 8 spec., 22 react.

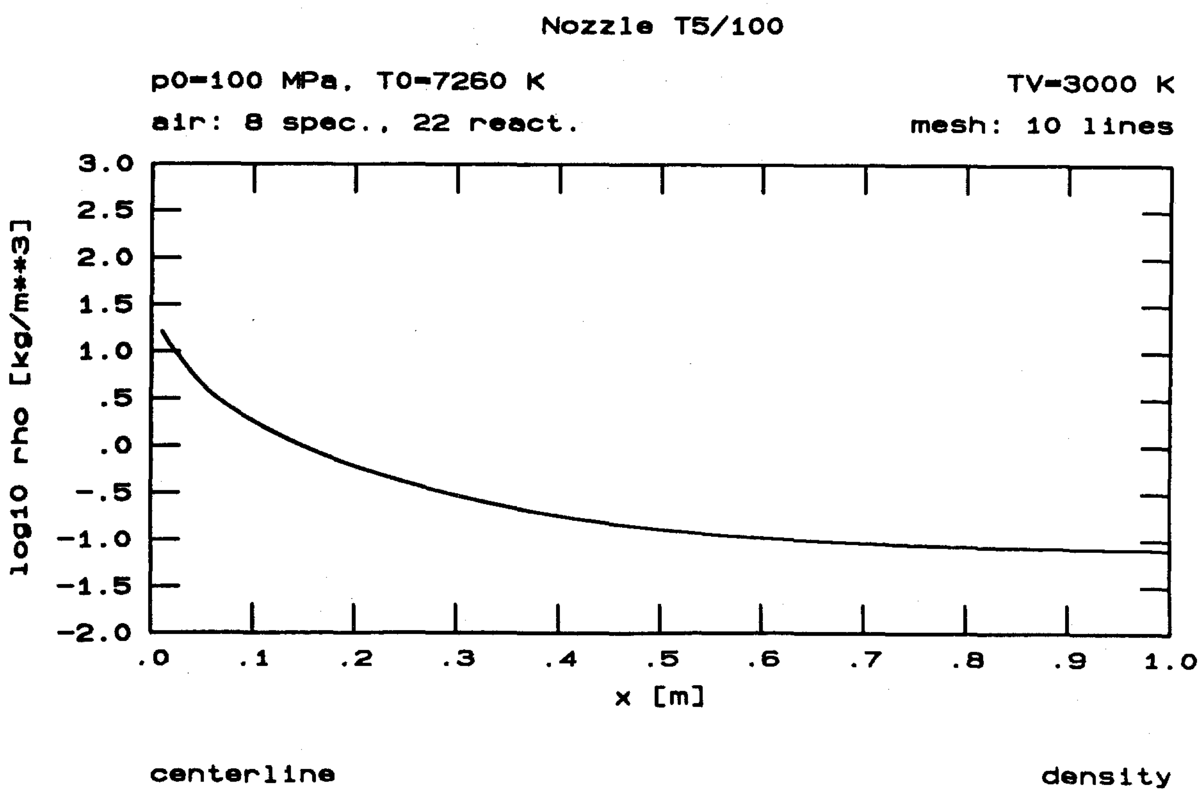
TV=3000 K
mesh: 10 lines

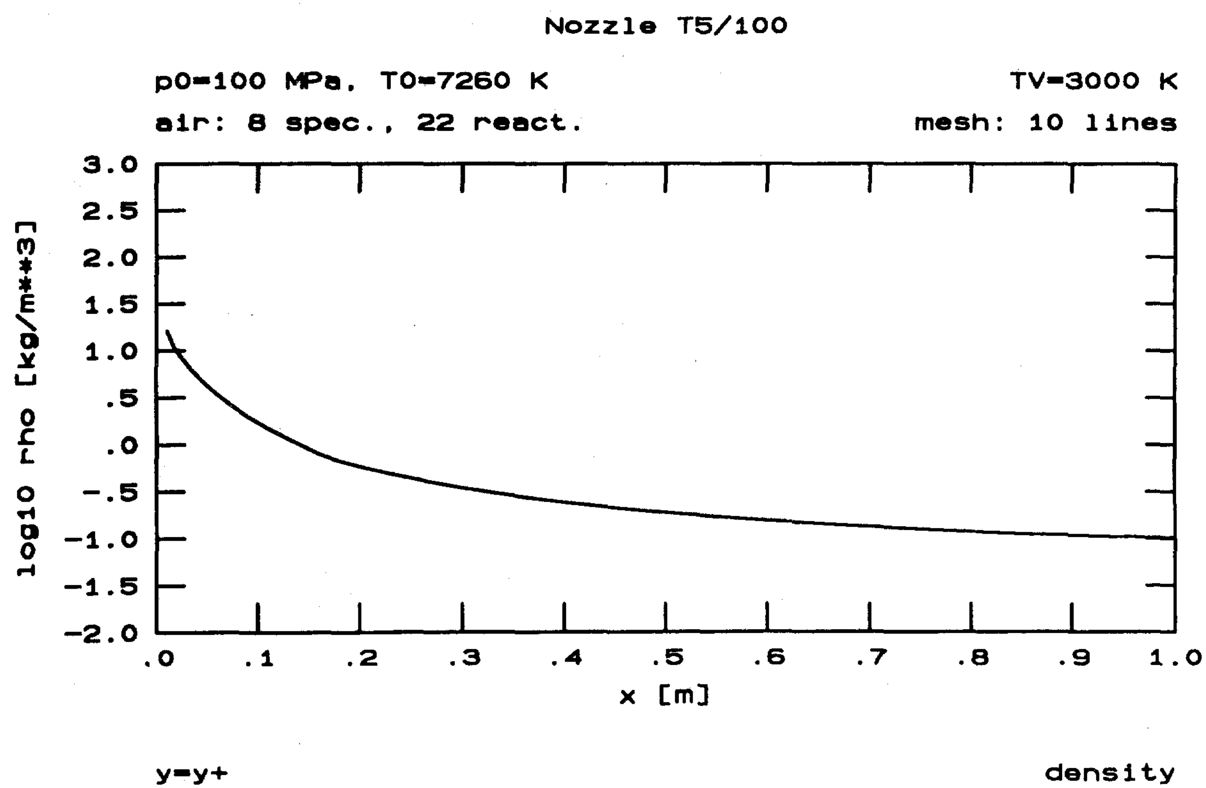


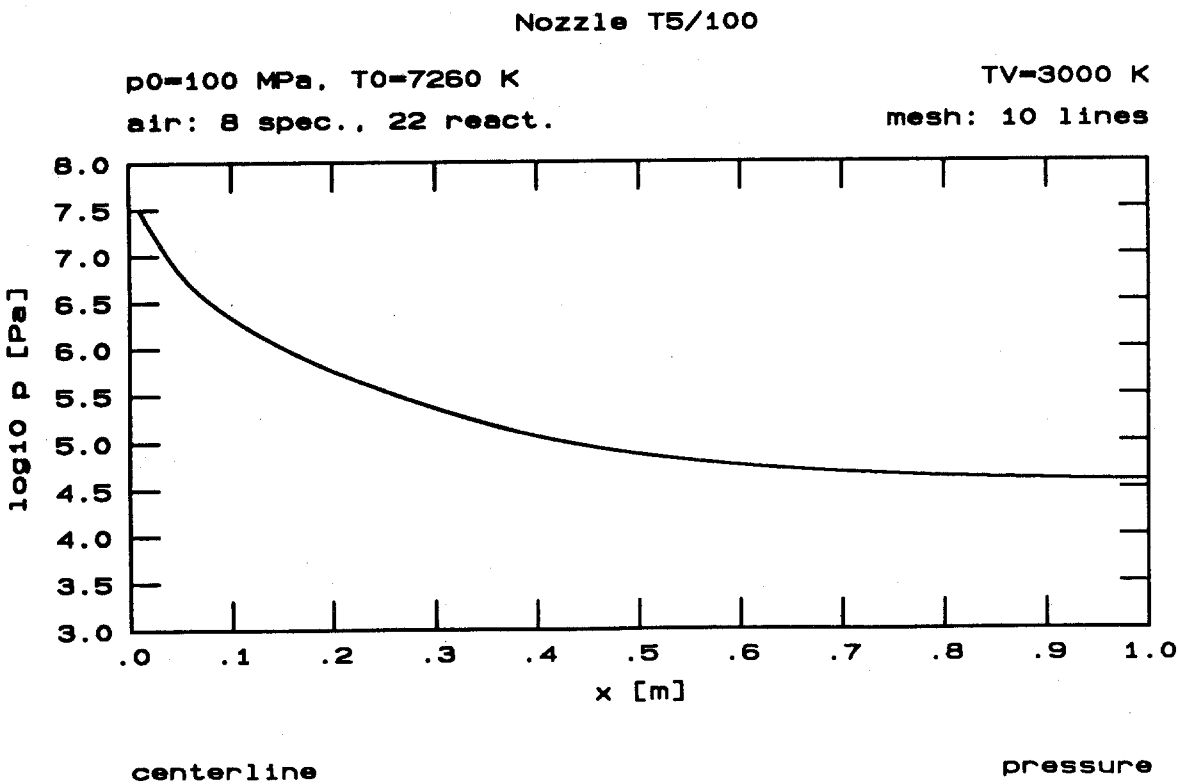
centerline

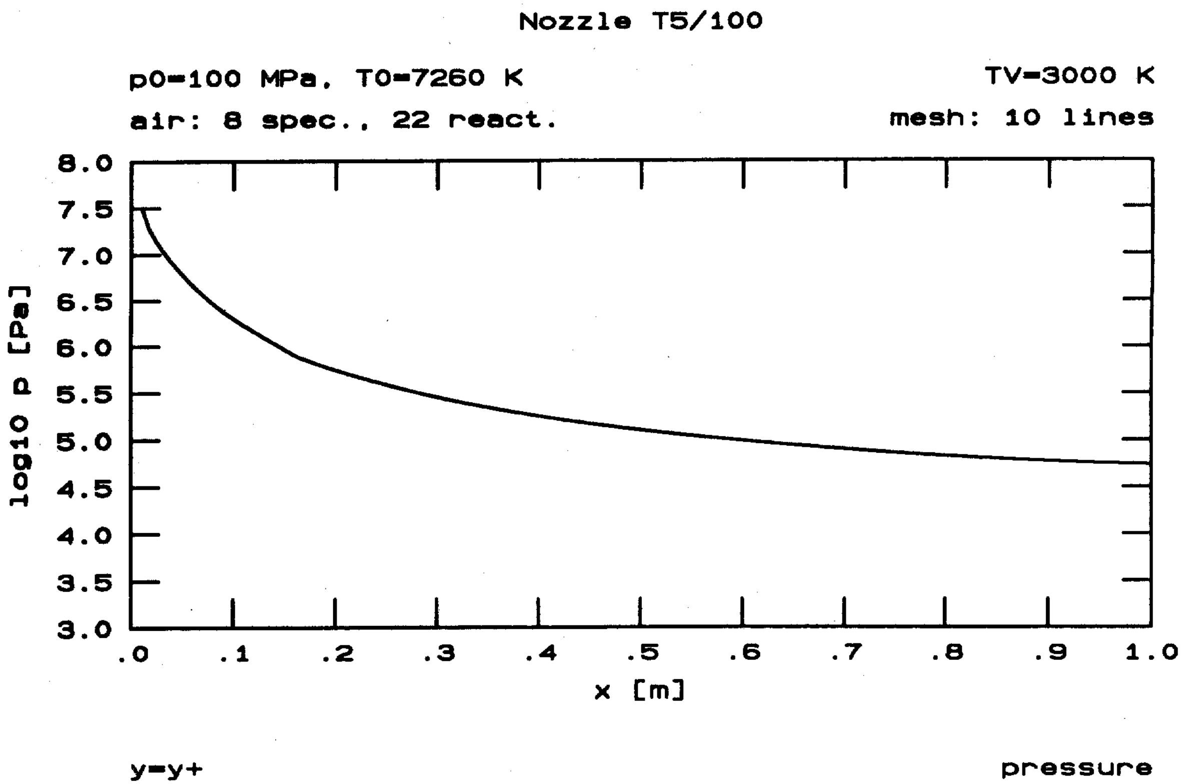
temperature

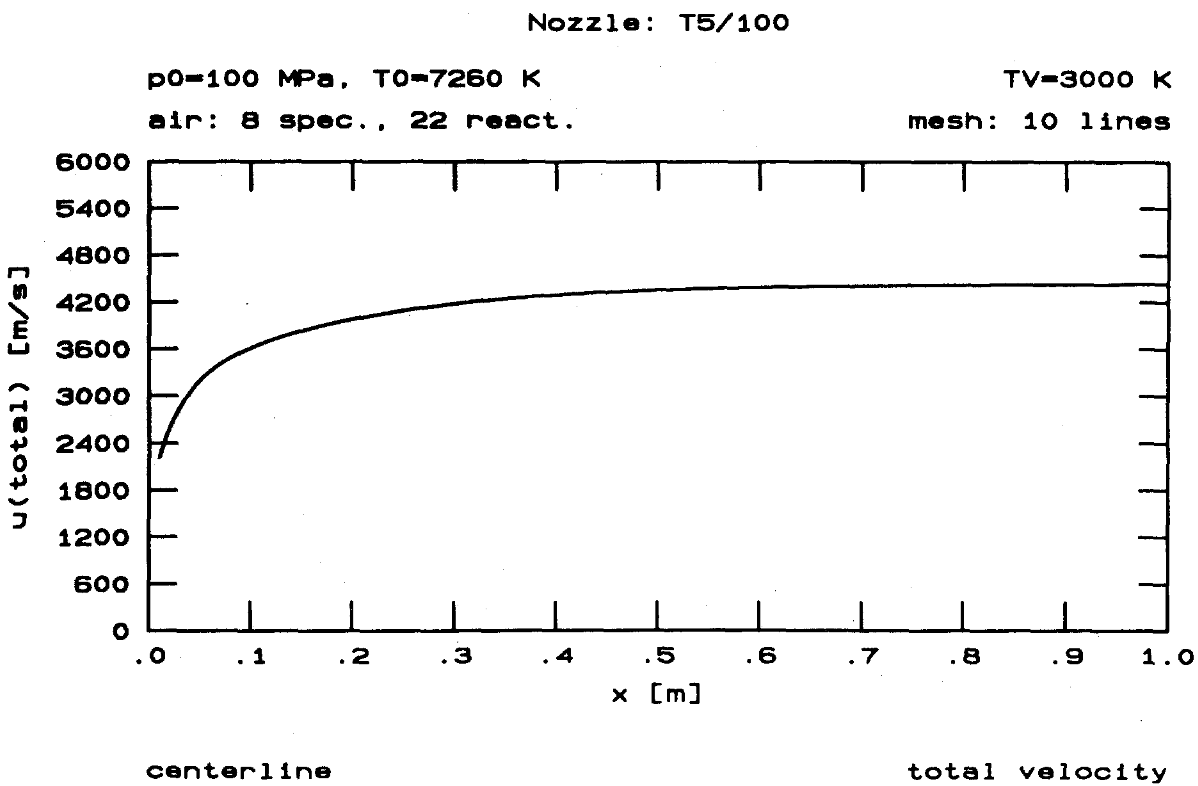

Nozzle: T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
T [K]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
temperature


Nozzle T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
3.0
2.5
2.0
1.5
1.0
.5
.0
-.5
-1.0
-1.5
-2.0
log10 rho [kg/m**3]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
density

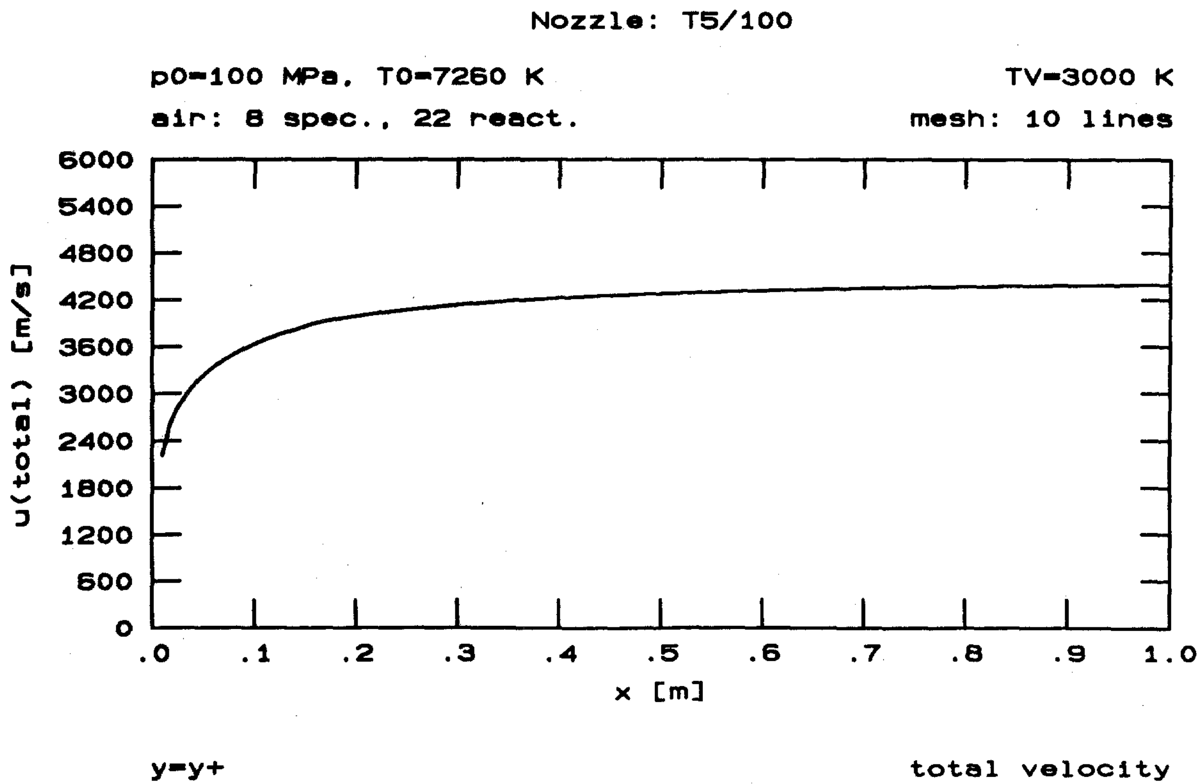

Nozzle T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 rho [kg/m**3]
3.0
2.5
2.0
1.5
1.0
.5
.0
-.5
-1.0
-1.5
-2.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
density

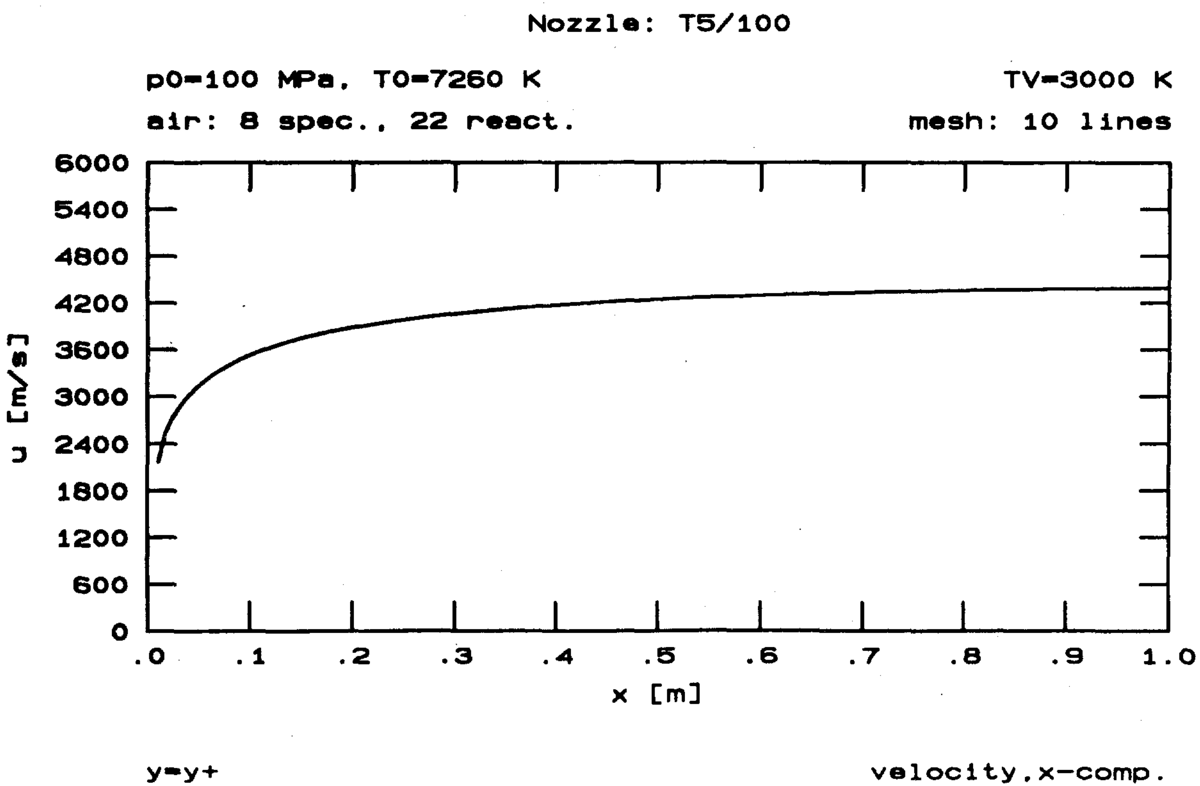

Nozzle T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
log10 p [Pa]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
pressure

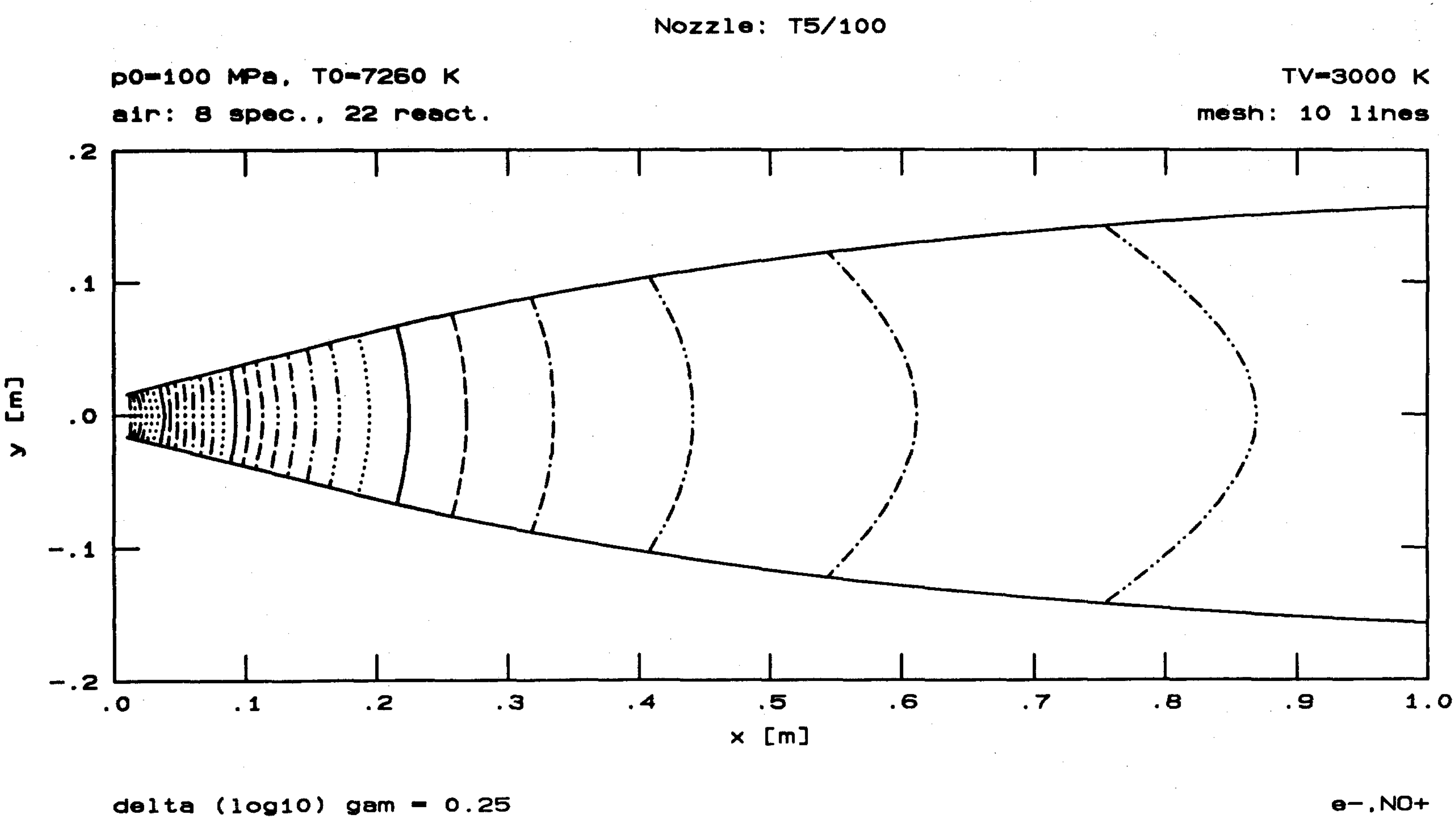

Nozzle T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
log10 p [Pa]
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
pressure



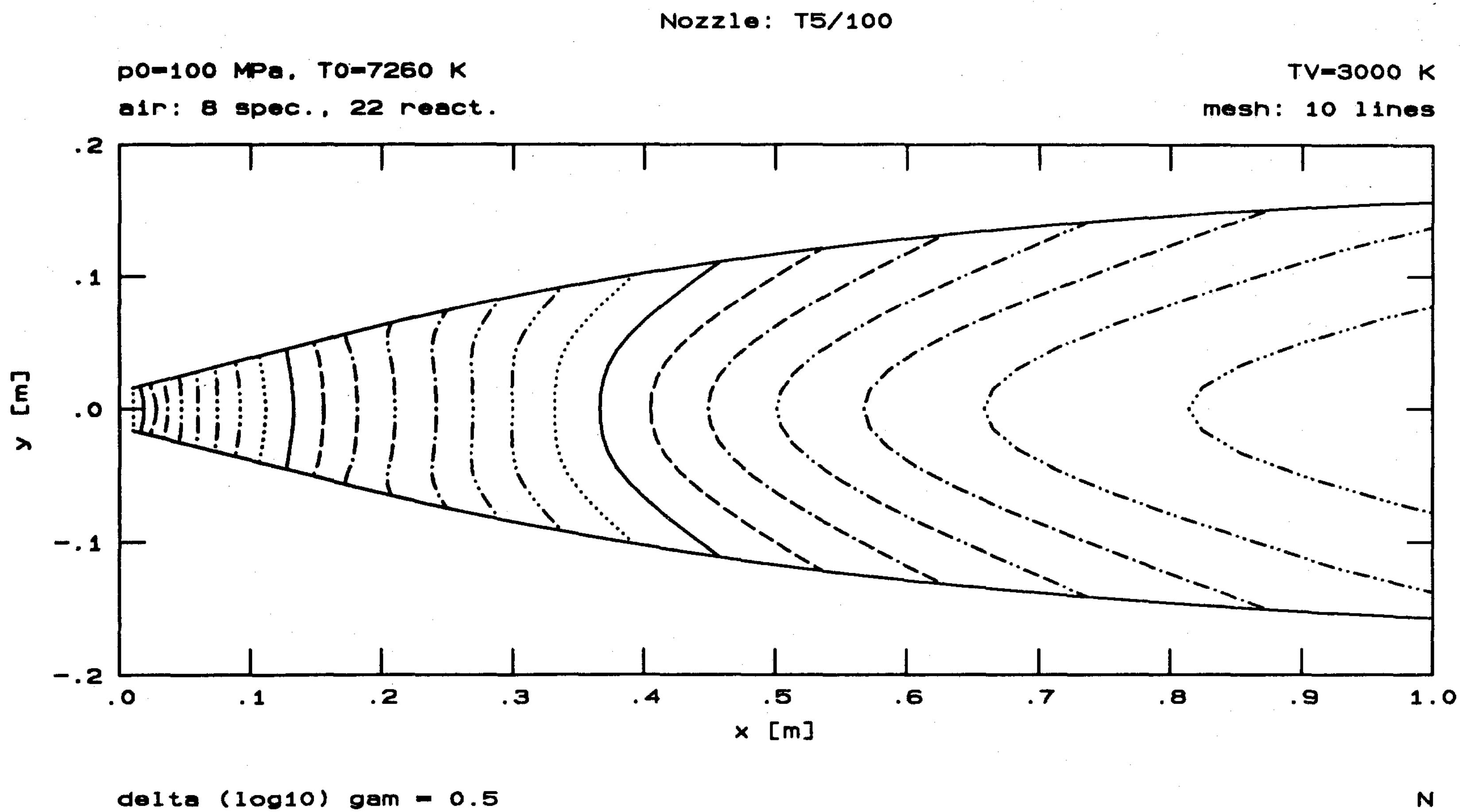
Nozzle: T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
u(total) [m/s]
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
centerline
total velocity


Nozzle: T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
u(total) [m/s]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
total velocity

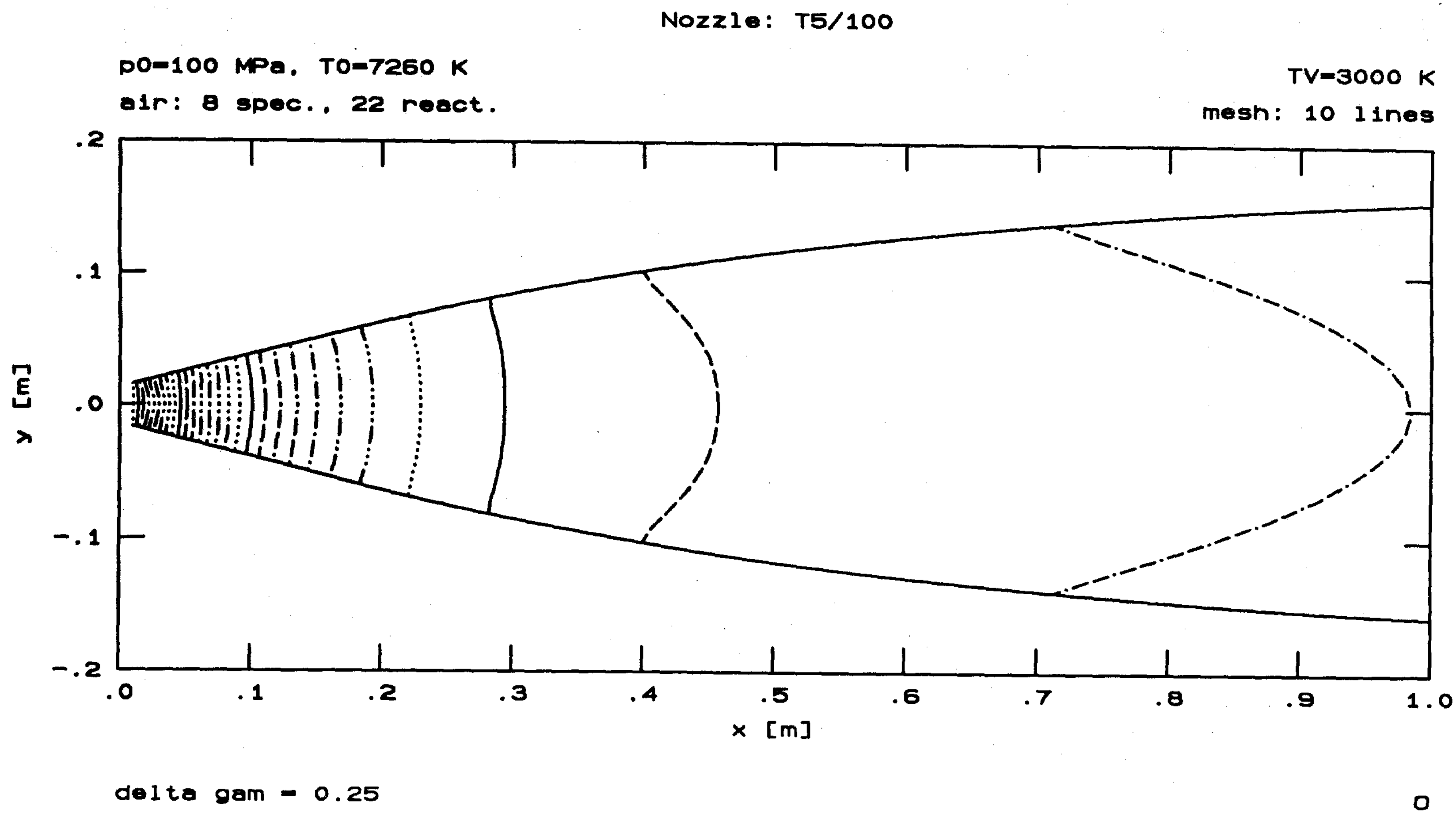

Nozzle: T5/100
p0=100 MPa, T0=7260 K
TV=3000 K
air: 8 spec., 22 react.
mesh: 10 lines
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
u [m/s]
.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x [m]
y=y+
velocity,x-comp.



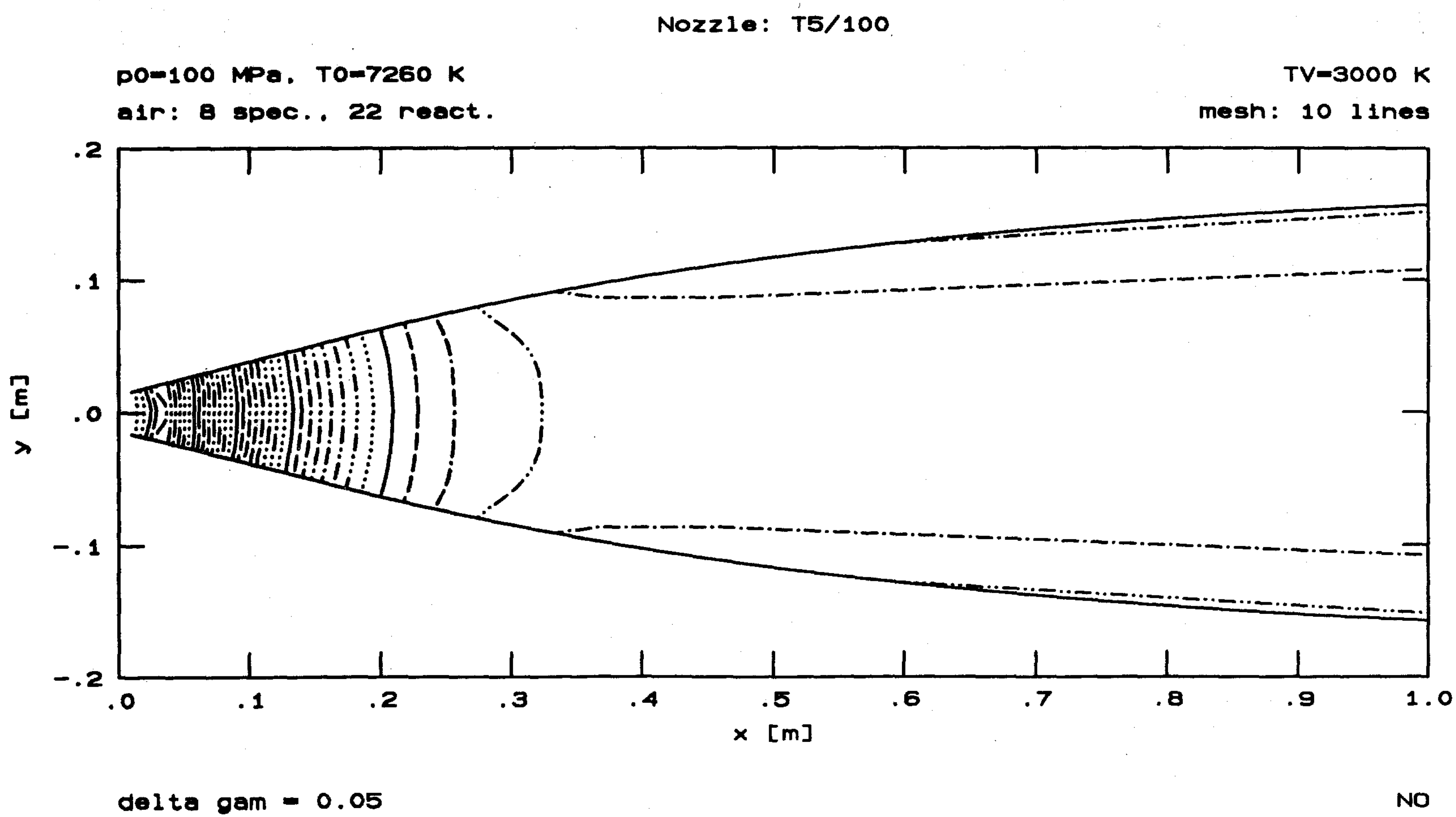
First upstream contour line: $\gamma_{NO+} = 1.4 \times 10^{-3}$ mol/kg;
farthest downstream one: $\gamma_{NO+} = 1.65 \times 10^{-6}$ mol/kg.



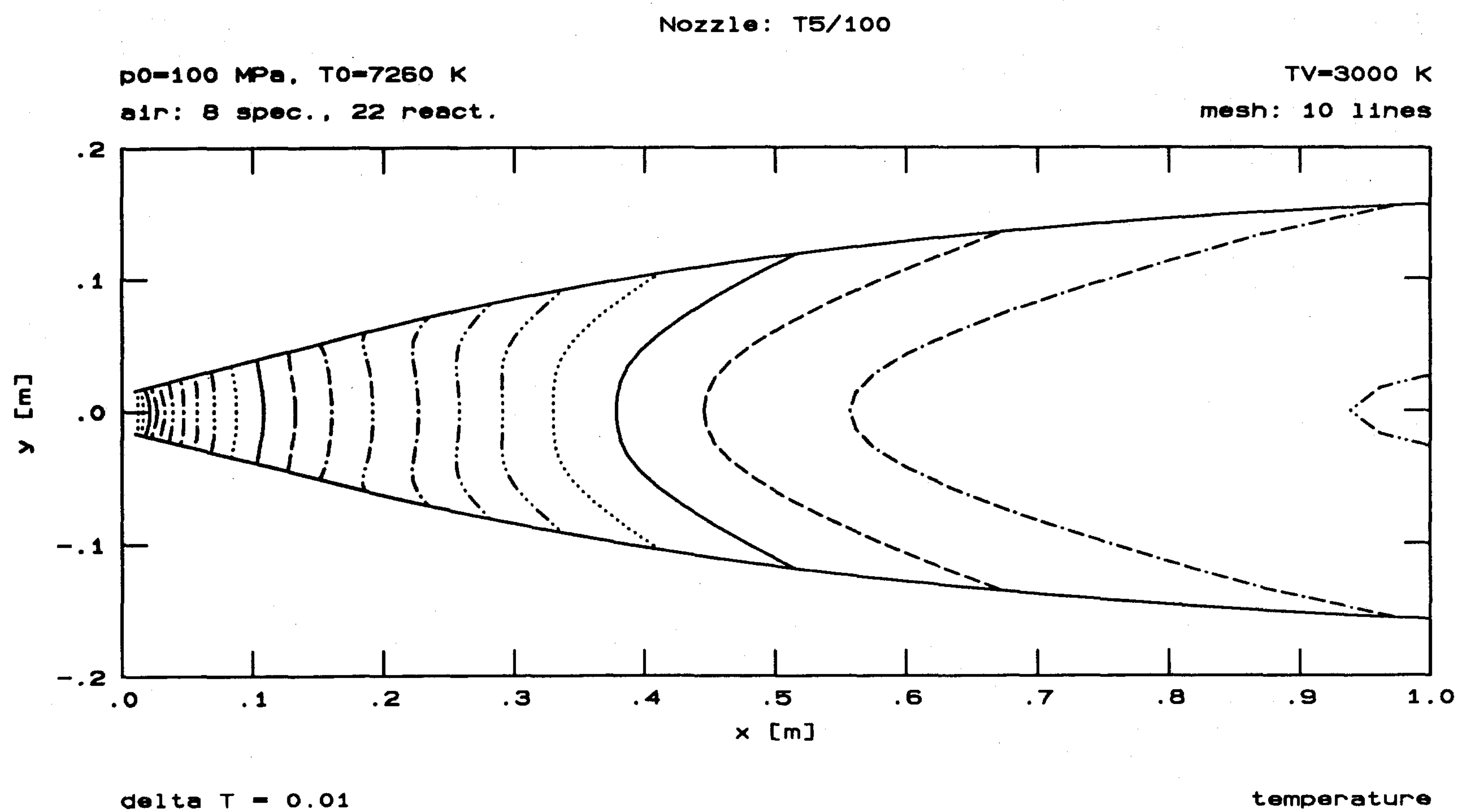
First upstream contour line: γ_N = 0.39 mol/kg;
farthest downstream one: γ_N= 3.95 x 10^{-6} mol/kg.



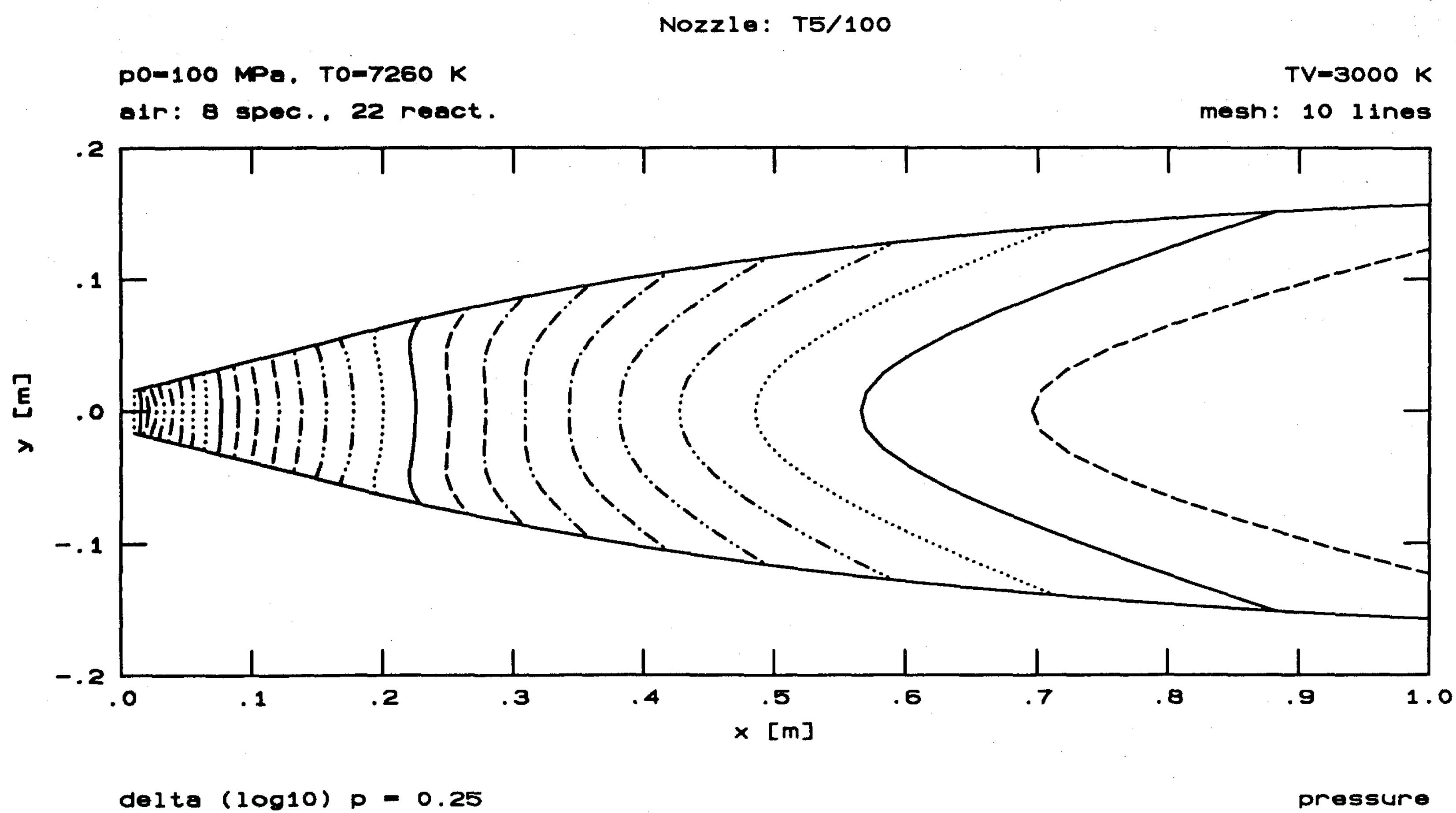
First upstream contour line: $\gamma_O = 7.8$ mol/kg; farthest downstream one: $\gamma_O = 1.05$ mol/kg.



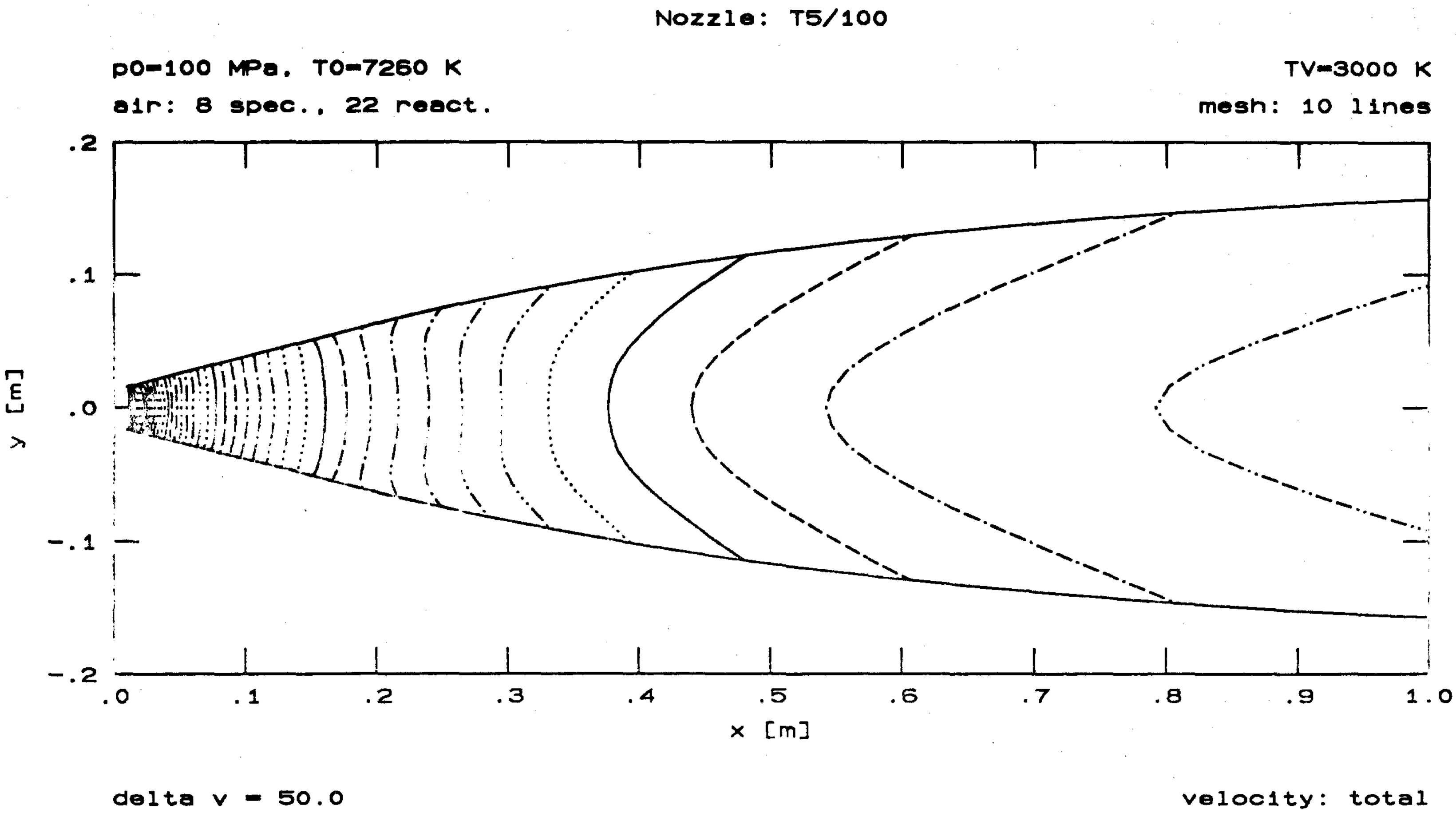
First upstream contour line: $\gamma_{NO} = 4.0$ mol/kg;
farthest downstream one: $\gamma_{NO} = 2.05$ mol/kg.



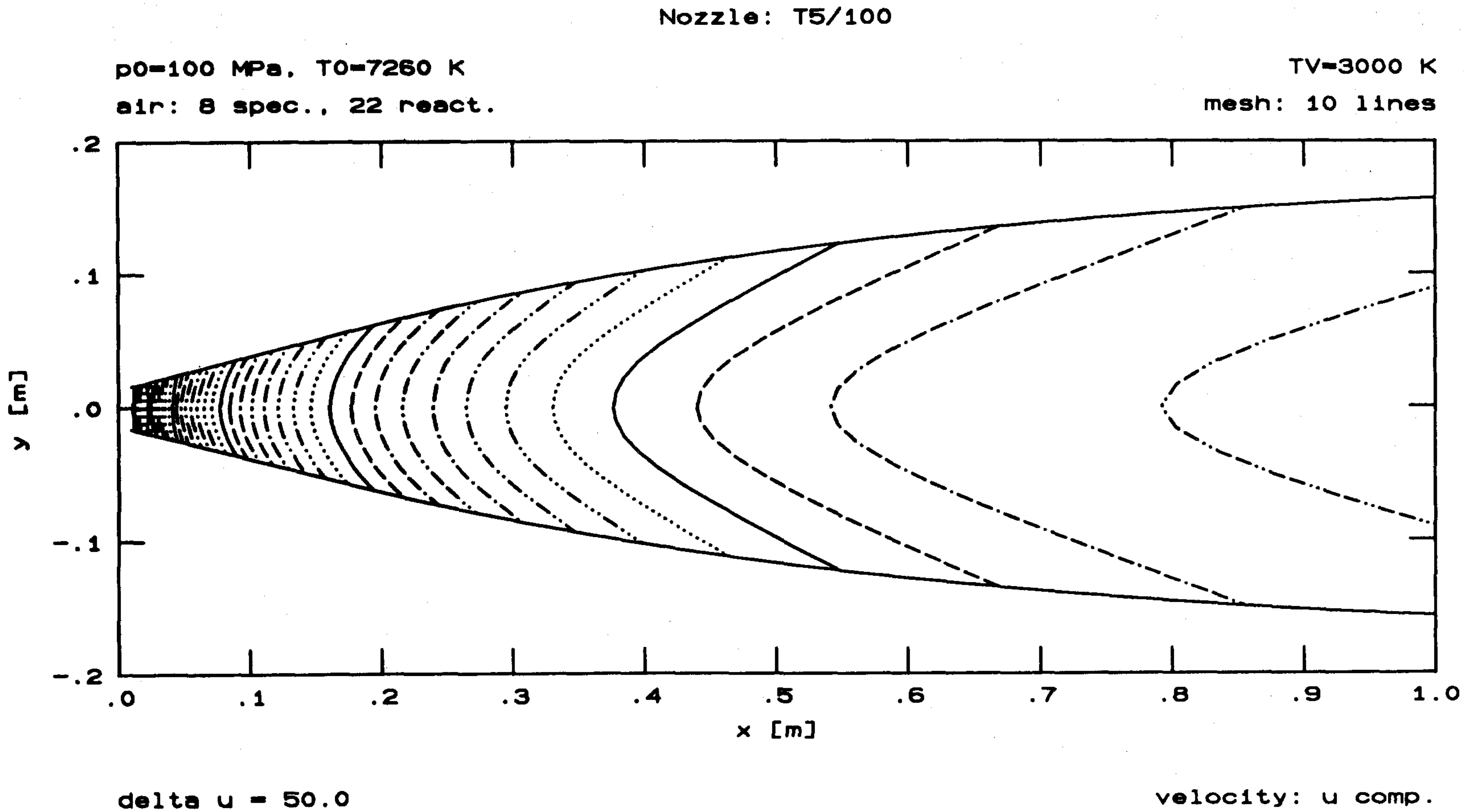
First upstream contour line: T = 5860 K;
farthest downstream one: T = 1660 K.



First upstream contour line: $p = 3.165 \times 10^7$ Pa;
farthest downstream one: $p = 47583.84$ Pa.



First upstream contour line: w = 2270 m/s;
farthest downstream one: w = 4420 m/s.



First upstream contour line: u = 2270 m/s;
farthest downstream one: u = 4420 m/s.